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TECHNOLOGY ADVANCEMENT OF AN OXYGEN GENERATION SUBSYSTEM

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M. K. Lee, K. A. Burke,
F. H. Schubert and R. A. Wynveen

May, 1979

Prepared Under Contract NAS2-9795

by

Life Systems, Inc.
Cleveland, OH 44122

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AMES RESEARCH CENTER
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FOREWORD

This report was prepared by Life Systems, Inc. for the National Aeronautics and Space Administration (NASA) Ames Research Center in accordance with the requirements of Contract NAS2-9795, "Development of a Static Feed Water Electrolysis Oxygen Generation Subsystem Breadboard." The period of performance for the program was December 1, 1977 to May 30, 1979. The objective of the program was to advance the Oxygen Generation Subsystem technology, based on static feed water electrolysis, and to demonstrate the maturity of the hardware development for future multicrew space missions.

Mr. Franz H. Schubert was Program Manager. Dr. Myon K. Lee was Project Manager. The personnel contributing to the program and their areas of responsibility are indicated below.

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LIST OF ACRONYMS

ARS	Air Revitalization System
ARX-1	Air Revitalization System (one-person, experimental)
ASU	Air Supply Unit
CHCS	Cabin Humidity Control Subsystem
C/M I	Control/Monitor Instrumentation
CRT	Cathode-Ray Tube
DM	Dehumidifier Module
EC/LSS	Environmental Control/Life Support System
ED	Electrolytic Dehumidification
EDC	Electrochemical Depolarized CO_2 Concentrator
EDCM	EDC Module
NGM	Nitrogen Generation Module
NSS	Nitrogen Supply Subsystem
OGS	Oxygen Generation Subsystem
ORS	Oxygen Recovery System
S-CRS	Sabatier CO_2 Reduction Subsystem
SFWE	Static Feed Water Electrolysis
SFWEM	Static Feed Water Electrolysis Module
3-FPC	Three-Fluid Pressure Controller
TSA	Test Support Accessories
WHS	Water Handling Subsystem

SUMMARY

Regenerative processes for the revitalization of spacecraft atmospheres are essential for making long-term manned space missions possible. One of the most important steps in this revitalization process is the reclamation of breathable oxygen from metabolically-produced carbon dioxide. Oxygen can be recovered in the form of water through the chemical reduction of carbon dioxide. The water is then electrolyzed to produce oxygen. Under this program an Oxygen Generation Subsystem based on water electrolysis was developed and tested to further advance the concept and technology of the spacecraft Air Revitalization System. Emphasis was placed on demonstrating the subsystem integration concept and hardware maturity at a subsystem level.

The Air Revitalization System consists of six subsystems and the centralized Control/Monitor Instrumentation. These subsystems are (1) an Oxygen Generation Subsystem, (2) a Carbon Dioxide Concentrator, (3) a Carbon Dioxide Reduction Subsystem, (4) a Water Handling Subsystem, (5) a Cabin Humidity Control Subsystem and (6) a Nitrogen Supply Subsystem. The Oxygen Generation Subsystem, part of the Water Handling Subsystem and centralized Control/Monitor Instrumentation were designed, fabricated and tested as part of the Air Revitalization System under this program. Developments of other subsystems of the Air Revitalization System were funded under separate NASA Ames Research Center programs and under the Contractor's internal research and development programs. This report outlines the development activities associated with the Oxygen Generation Subsystem, the Water Handling Subsystem and the centralized Control/Monitor Instrumentation. Emphasis is placed on the developments of the Oxygen Generation Subsystem and its technology.

The primary objective of the Oxygen Generation Subsystem is to produce oxygen for metabolic consumption. The byproduct hydrogen is used in processes for concentrating and reducing carbon dioxide. The Oxygen Generation Subsystem developed under the present program employs the Static Feed Water Electrolysis concept. The static feed-based Oxygen Generation Subsystem consists basically of three main parts: an electrochemical module, a pressure controller and a water feed tank. The generation of oxygen and hydrogen occurs in a series of electrolysis cells forming an electrochemical module. The cells use an aqueous solution of potassium hydroxide retained in a porous asbestos matrix. Water feed into the individual cells is achieved statically, minimizing moving parts for increased subsystem reliability.

The Oxygen Generation Subsystem developed as part of this program was designed to deliver oxygen at a rate of 1.46 kg/d (3.22 lb/d) which included 0.83 kg/d (1.84 lb/d) for metabolic consumption of one person and 0.63 kg/d (1.38 lb/d) for other requirements such as cabin leakage makeup. The 12-cell electrochemical module operated at a current density of 197 mA/cm^2 (183 ASF), temperature of 339 K (150 F) and pressure of 1,068 kPa (155 psia). The active electrode area of a single cell is 92.9 cm^2 (0.1 ft^2). The electrolysis cells were interconnected in series electrically. All fluid connections were made in parallel. The pressure controller combined, in a single assembly, the sensors and actuators necessary to control and monitor fluid pressure levels and differentials during all operating modes and transitions, including steady-state operation, startup and shutdown.

The primary function of the Water Handling Subsystem is to ensure that a supply of water exists for the Oxygen Generation Subsystem. The principal components in the Water Handling Subsystem are a water storage tank and a deionizer. The deionizer contains both a charcoal and an ion-exchange resin bed for removing iodine ions and dissolved carbon dioxide from the feed water of the Oxygen Generation Subsystem. Water comes either from the Carbon Dioxide Reduction and Cabin Humidity Control Subsystems or from an external source.

The centralized Control/Monitor Instrumentation employs an advanced instrumentation concept which is highlighted by minicomputer-based control and monitoring. The function of the Control/Monitor Instrumentation is to provide automatic mode and mode transition control, automatic shutdown provisions for self-protection, provisions for monitoring system parameters and provisions for interfacing with ground test instrumentation.

An extensive test program including components, subsystem and integrated system testing was completed. The overall objectives of the test program were to (1) prove the integration concept of the Air Revitalization System, (2) further advance the Oxygen Generation Subsystem technology, and (3) demonstrate the hardware maturity of the Oxygen Generation Subsystem components such as electrolysis cells, modules and the Three-Fluid Pressure Controller. Integrated testing of the experimental Air Revitalization System was conducted for a period of 120 days and included testing at the component, subsystem and total system levels.

A total of 480 hours of successful integrated operation was achieved with the Air Revitalization System. Of the total normal operation, two seven-day periods of uninterrupted operation were achieved. A single cell with one of the super electrodes (WAB-6) was subjected to endurance testing. A total of 8,650 hours continuous operation has been accumulated at the conclusion of the current program. Cell voltages during the period of endurance testing remained stable in the range of 1.46 to 1.50 V. Operating conditions were set nominally at 352 K (175 F), 161 mA/cm^2 (150 ASF) and ambient pressure. A 12-cell module using the super electrodes (WAB-6) was tested at 355 K (180 F), 993 kPa (144 psia) and 161 mA/cm^2 (150 ASF). Individual cell voltages varied in the range of 1.47 to 1.50 V, indicating the performance of the super electrodes is reproducible. In addition, the pressure controller and another 12-cell module using the advanced electrodes (WAB-5) were extensively tested to determine the hardware maturity.

It is concluded from the results reported herein that the integration concept of the Air Revitalization System is feasible. Hardware and technology of the Oxygen Generation Subsystem has been demonstrated to be close to the preprototype level. Continued development of the oxygen generation technology is recommended to further reduce the total weight penalties of the Oxygen Generation Subsystem through optimization. Successful completion of this development will produce timely technology necessary to plan future advanced environmental control and life support system programs and experiments.

PROGRAM ACCOMPLISHMENTS

Under Contract NAS2-9795 the following major accomplishments were made in technology and hardware development of the Oxygen Generation Subsystem (OGS):

- Designed and fabricated a one-person capacity engineering breadboard OGS.
- Integrated and tested the OGS with an experimental Air Revitalization System (ARX-1). Proved the integration concept of the Air Revitalization System (ARS) is feasible.
- Demonstrated the superior performance of advanced water electrolysis cells (e.g. cell voltages of 1.45 to 1.50 V at 161 mA/cm^2 (150 ASF) and 340 K (153 F)) is stable and reliable over a long period of time (greater than 8,650 h).
- Demonstrated that the super electrode (WAB-6) performance was retained through scale-up from single cells to a 12-cell module.
- Demonstrated the hardware maturity of the OGS components such as electrodes, cells, modules and a Three-Fluid Pressure Controller (3-FPC).
- Developed a Water Handling Subsystem (WHS). Integrated and tested the WHS with the ARX-1.
- Developed automatic, centralized Control/Monitor Instrumentation (C/M I) for the ARX-1. The central C/M I provided single-button startup, automatic process control and monitoring and automatic fail-safe shutdown.

INTRODUCTION

Regenerative processes for the revitalization of spacecraft atmospheres are essential for making long-term manned space missions possible. An important step in this overall process is the reclamation of oxygen (O_2) for metabolic consumption through the electrolysis of water. The byproduct hydrogen (H_2) is used to produce water from metabolically-generated carbon dioxide (CO_2). The water is then electrolyzed to produce O_2 and H_2.

An Oxygen Generation Subsystem (OGS) based on the static feed water electrolysis (SFWE) concept has been recognized as a design capable of efficient, reliable O_2 generation with few subsystem components. The static feed concept has evolved over the past 12 years under the National Aeronautics and Space Administration (NASA) and Life Systems, Inc. (LSI) sponsorship. Recent developments at LSI allow substantial reductions in the operating voltage levels of water electrolysis cells. This state-of-the-art advancement is significant since the OGS is the largest power consumer of a regenerative Environmental Control/Life Support System (EC/LSS). The electrolysis power is directly related to the cell voltage.

Background

Prior development efforts of water electrolysis cells, modules and subsystems have included those that use the static water feed concept.[1-4] Subsystems using this concept have demonstrated an inherent simplicity and long operating life capabilities.[3,5] The OGS, using SFWE, has the potential for the lowest power-consuming electrolysis subsystem due to the alkaline electrolyte used.[1,6] Various approaches to the static feed design and the results of extensive test programs identified necessary key subsystem improvements.[2] These improvements were made and incorporated into the design of the hardware being developed by LSI. Specific improvements included:[4,7]

- Reduction in electrolysis cell voltage
- Elimination of water feed compartment degassing
- Elimination of condenser/separators which are characteristic of other applicable water electrolysis subsystems
- Elimination of aerosols in the product gas streams

In 1977 a significant reduction in state-of-the-art cell voltage levels was achieved with a Contractor-developed catalyst for the O_2-evolving electrode (Figure 1). Under a previous program (Contract NAS2-8682) sponsored by NASA, a total of 136 days of single cell operation were accumulated with representative cell voltage levels averaging 1.45 V at 161 mA/cm^2 (150 ASF) and 355 K (180 F) being demonstrated.[4]

Program Objectives

The objective of the present program was to further advance the OGS technology with major emphasis on demonstrating the subsystem integration concept and hardware maturity at a subsystem level. Specific objectives were to:

1. Design and fabricate an engineering breadboard OGS based on SFWE.
2. Integrate and test the OGS with an ARX-1 to prove the feasibility of the subsystem integration concept.
3. Demonstrate the superior performance of previously-developed, advanced water electrolysis cells at both the single cell and scaled-up module levels.
4. Demonstrate the hardware maturity of the OGS at a subsystem level by endurance testing the ARX-1.

The objectives of the program were met.

Program Organization

To meet the above objectives, the program was divided into five tasks plus the documentation and program management functions. These five tasks were:

(1) References at end of this report.

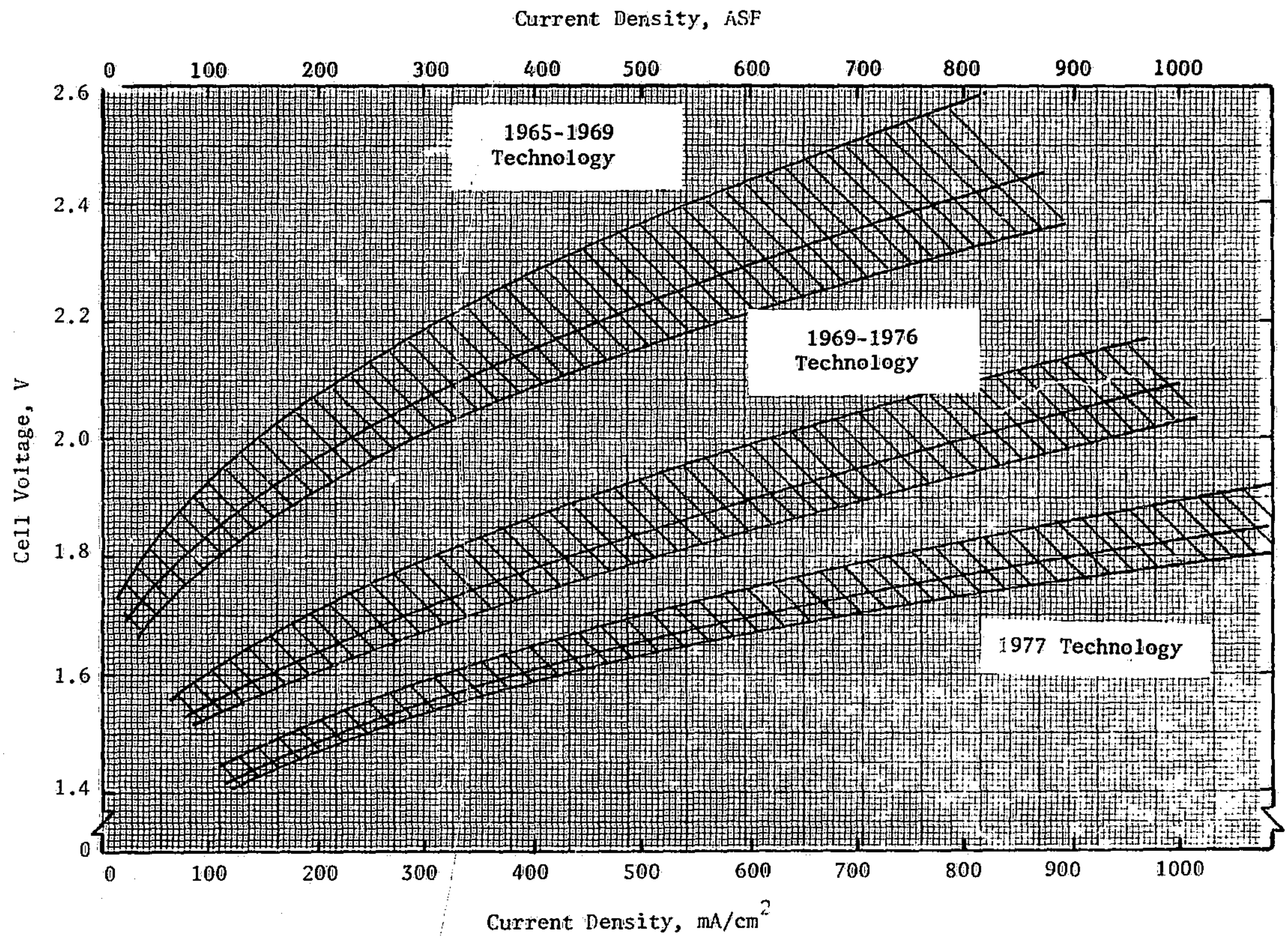


FIGURE 1 MAJOR ELECTRODE/CATALYST PERFORMANCE IMPROVEMENTS

Task	Description
1.0	Design, fabricate and assemble the OGS, the WHS and the C/M I. Integrate the subsystems into the ARX-1.
2.0	Develop and calibrate Test Support Accessories (TSA) to enable operation of the OGS within the ARX-1.
3.0	Establish, implement and maintain a mini-Product Assurance program.
4.0	Perform a variety of module, subsystem and integrated ARX-1 testing.
5.0	Complete supporting research and development effort to further expand the OGS technology.

AIR REVITALIZATION SYSTEM DEVELOPMENT

A prior program demonstrated that the OGS could be successfully integrated with other air revitalization subsystems into a laboratory breadboard Oxygen Recovery System (ORS) at the one-person level.[4] A 30-day endurance test of the OGS, integrated with an Electrochemical Depolarized CO_2 Concentrator (EDC) and a Sabatier-based CO_2 Reduction Subsystem (S-CRS), showed that the three subsystems would remove and reduce the metabolically-generated CO_2 and produce the required O_2 level for one person in a spacecraft application.

The next step in the development of the OGS for the spacecraft ARS was completed as part of the program activities. This activity was the design, fabrication and test of the ARX-1 which incorporated the OGS. The philosophy for this "next-step" approach was different than in previously integrated laboratory breadboard systems where each of the subsystems: (1) were self-contained, (2) had their own C/M I, (3) were started and shut down independently, (4) were tied together by appropriate interfaces and (5) contained redundant components.

The self-contained system (versus subsystem) approach selected for the ARX-1 was based on reducing subsystem interfaces, eliminating redundant components and utilizing the products (i.e. heat, electrical power, fluids) of one subsystem in another. As an example, the H_2 generated by the OGS is used by the EDC and S-CRS. Also, the C/M I was designed as a single unit that would operate all components as a single system by providing for one-button startup/shutdown of all ARS functions, automatic sequencing and control and monitoring for self-protection and safe operation. The objective of this portion of the program activities was to demonstrate, through actual testing, the validity of the integration approach as well as verify the advantages, identify new ones and isolate shortcomings for future correction.

Concept Description

Figure 2 is a block diagram of the self-contained ARS concept. The three principal subsystems (OGS, EDC and S-CRS) needed to provide O_2 to and remove CO_2 from the crew space are shown.

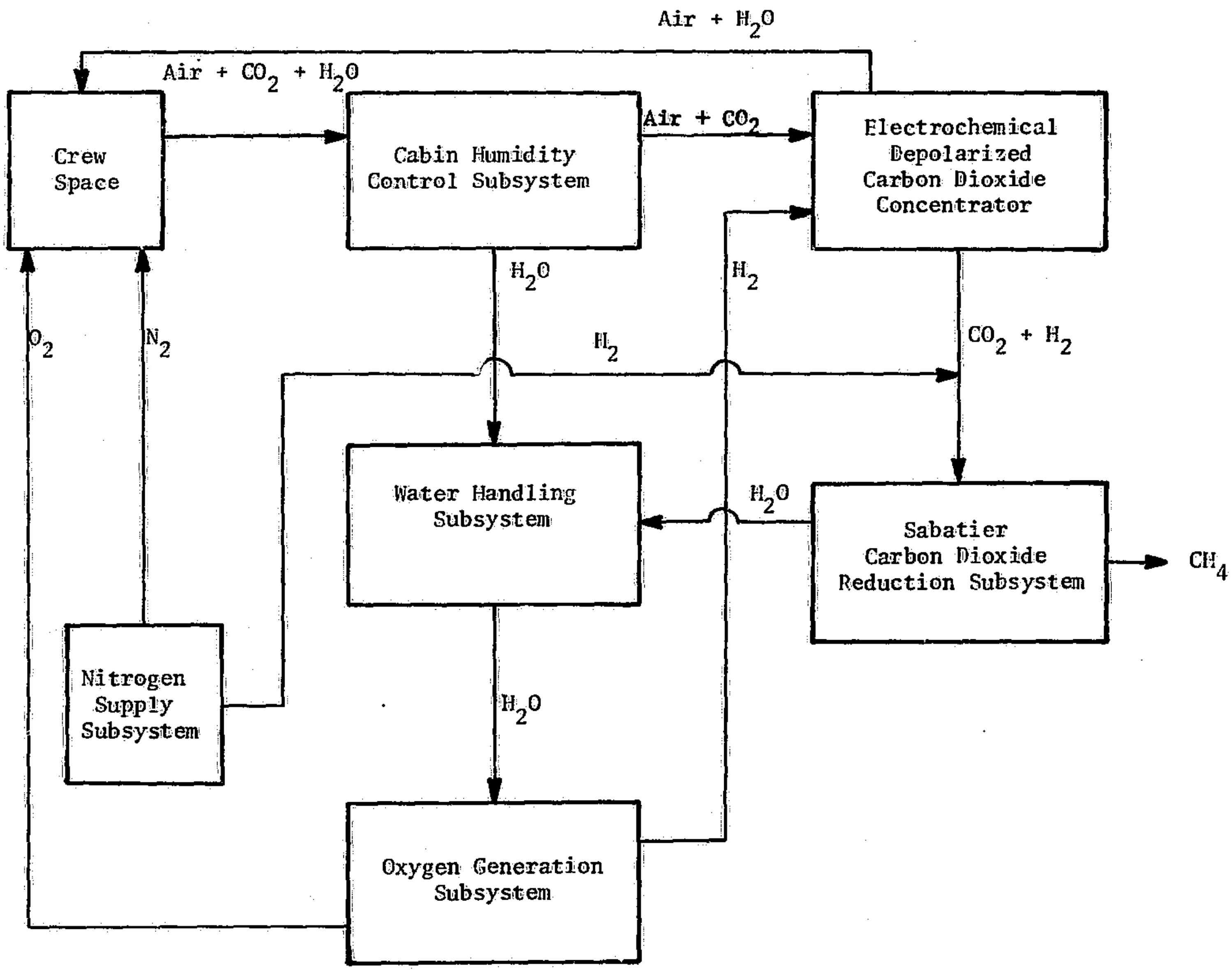


FIGURE 2 AIR REVITALIZATION SYSTEM BLOCK DIAGRAM

Additional subsystems and components are needed to provide other air revitalization functions. A Nitrogen (N_2) Supply Subsystem (NSS) using decomposition of hydrazine (N_2H_4) provides for N_2 lost through cabin leakage. Also, the NSS supplies extra H_2 required by the S-CRS. A Cabin Humidity Control Subsystem (CHCS) is used to supply conditioned air to the EDC at a humidity level which results in optimum efficiency and to remove the metabolically- and EDC-produced moisture from the cabin air. A WHS collects, stores and distributes process water to the OGS. Finally, the centralized C/M I provides for automatic, integrated operation. Table 1 lists the design requirements established for the ARX-1. Of particular note is the net O_2 generation rate which includes O_2 for crew consumption and a provision for overboard leakage.

The activities associated with the development of the EDC, CHCS, NSS and portions of the C/M I for the ARX-1 were funded under separate NASA Ames Research Center programs.[8-10] The development associated with the S-CRS and its major components were supported by Contractor funds. Only the OGS development and part of both the WHS and C/M I developments were funded through this contract.

Details of the OGS, WHS and C/M I for the ARX-1 are discussed in the Subsystem Development section of this report. Only highlights of the ARX-1 design are described below.

Hardware Description

The mechanical hardware of the ARX-1 was packaged as a single unit as shown in Figure 3. Identified in Figure 3 are the OGS module, the Sabatier reactor and modules of the EDC and NSS. Components of the WHS are distributed throughout the system. This breadboard system has a total weight of 281 kg (619 lb) and occupies an evelope of 71 x 96 x 114 cm (28 x 38 x 45 in). The ARX-1 mechanical hardware with its C/M I and TSA, which comprise the test facility, is shown in Figure 4. A detailed flow schematic of the ARX-1 is presented in Appendix 1.

The C/M I of the ARX-1 employs an advanced instrumentation concept which is highlighted by minicomputer-based controls and monitors. The C/M I was packaged in a separate enclosure shown in Figure 5. The function of the C/M I is to provide automatic mode and mode transition control, automatic shutdown provisions for self-protection, system parameter monitoring and ground test instrumentation interface.

SUBSYSTEM DEVELOPMENTS

Major program activities were focused on the development of the OGS. The following sections describe the OGS, the WHS and the C/M I. Emphasis is placed on the OGS development.

Oxygen Generation Subsystem

The primary objective of an OGS is to produce O_2 for metabolic consumption. The byproduct H_2 is used in processes for concentrating and reducing CO_2. The OGS developed employed the SFWE concept.

TABLE 1 ONE-PERSON AIR REVITALIZATION SYSTEM DESIGN REQUIREMENTS

Crew Size	1
CO_2 Removal Rate, kg/d (lb/d)	1.00 (2.20)
O_2 Generation Rate, kg/d (lb/d)	1.03 (2.27)[a]
Water Vapor Removal Rate, kg/d (lb/d)	1.80 (3.96)
Liquid Water Production Rate, kg/d (lb/d)	1.49 (3.27)
CH_4 Production Rate, kg/d (lb/d)	0.36 (0.79)
N_2 Production Rate, kg/d (lb/d)	0.60 (1.32)

(a) Consists of 0.84 kg/d (1.84 lb/d) O_2 metabolic and 0.19 kg/d (0.43 lb/d) for leakage requirements.

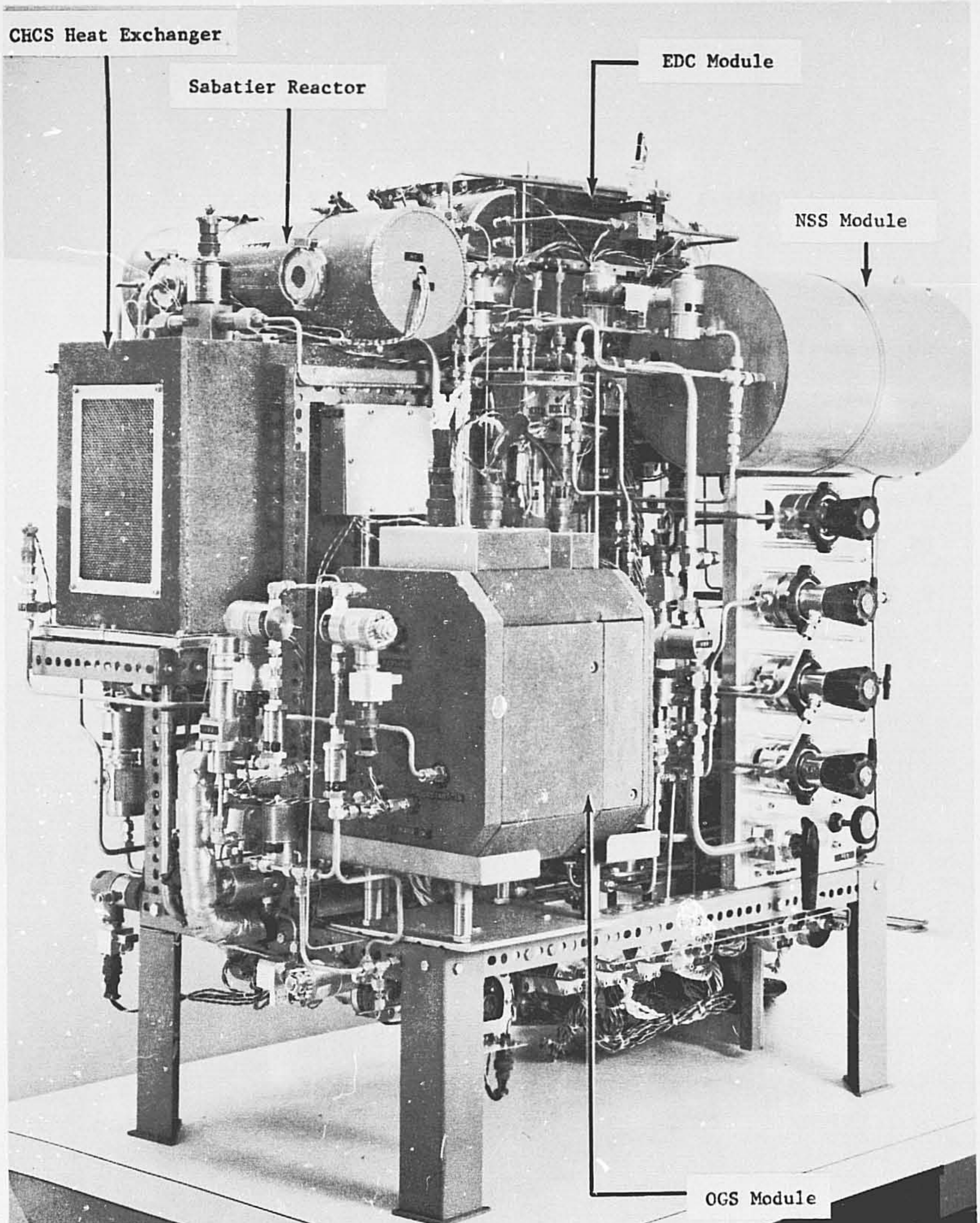


FIGURE 3 ARX-1 MECHANICAL HARDWARE

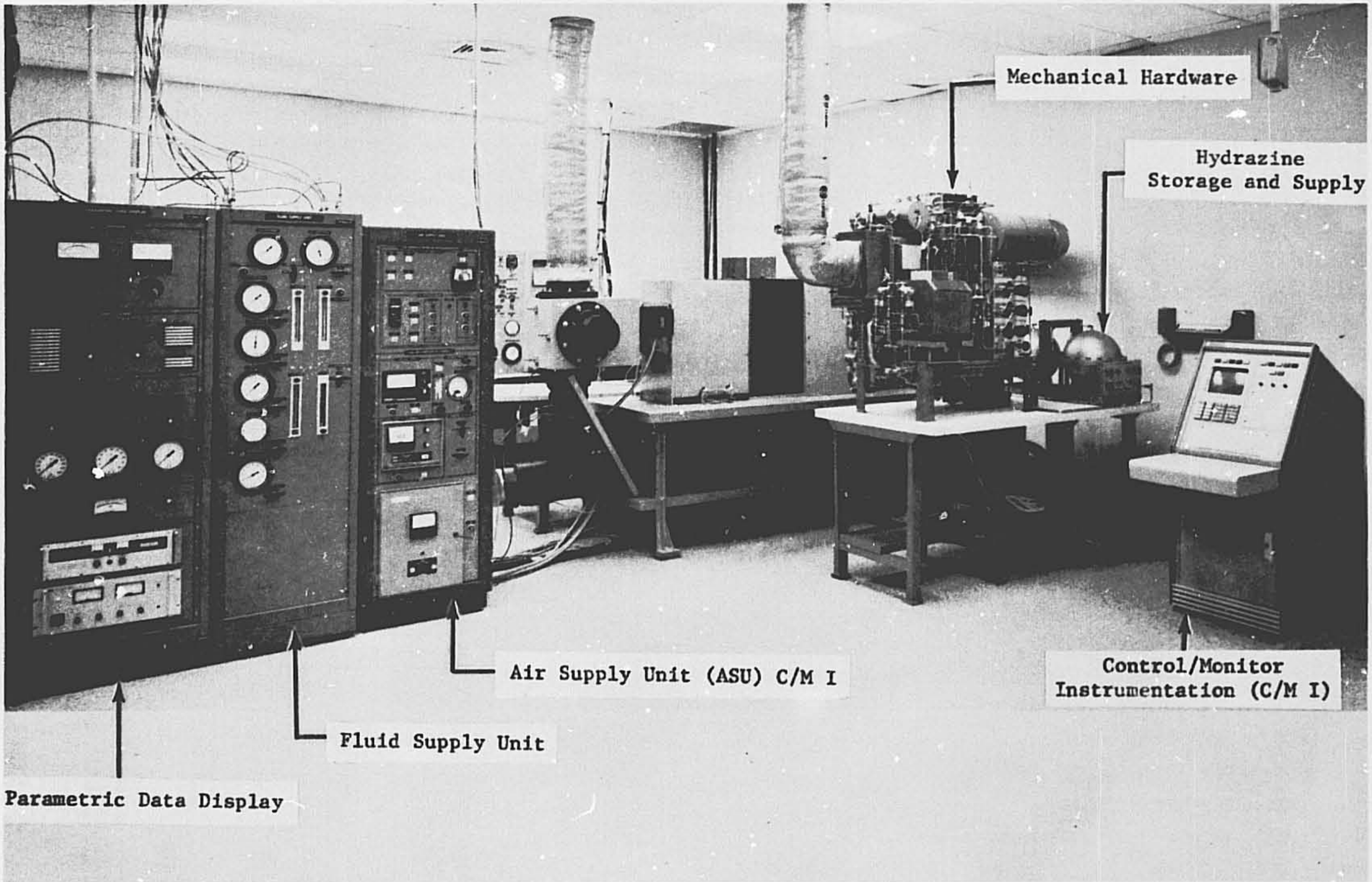


FIGURE 4   ARX-1 TEST FACILITY

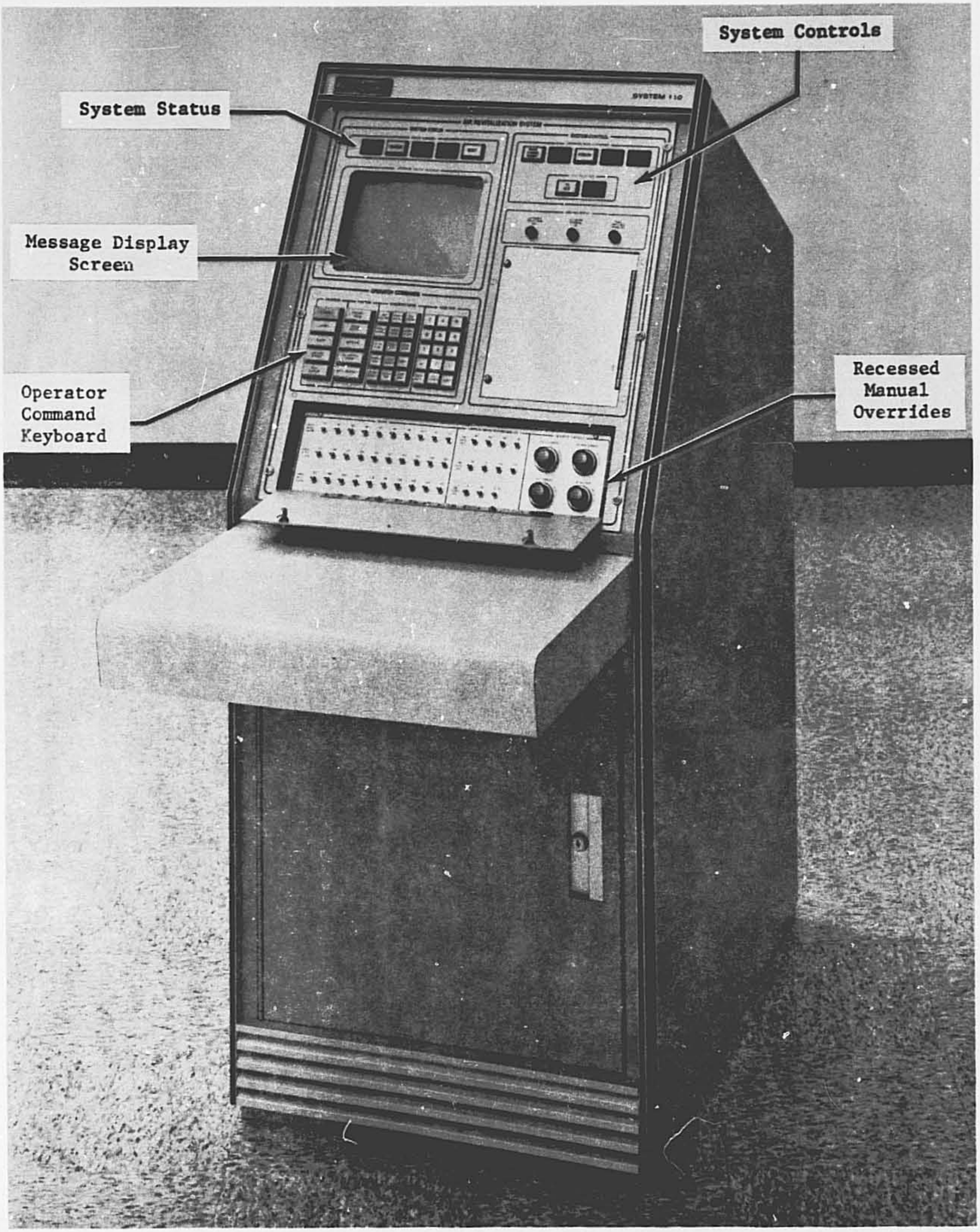


FIGURE 5 ARX-1 CONTROL AND MONITOR INSTRUMENTATION

Static Feed Water Electrolysis

Detailed descriptions of the SFWE process have been discussed previously.[2] The following summarizes its concept and the electrochemical processes.

Static Feed Water Electrolysis Concept. A conceptual schematic of an OGS based on the SFWE concept is shown in Figure 6. The subsystem consists of three main parts: an electrochemical module, a water feed tank and a pressure controller.

The module generates O_2 and H_2 from water supplied by the water feed tank. The water feed tank is cyclically filled as required from the collection points within the EC/LSS (e.g., CO_2 Reduction Subsystem). The pressure controller (a) maintains the absolute pressure of the subsystem, (b) maintains the pressure differentials required to establish and maintain fluid (H_2O and electrolyte) locations within the individual cells of the module and (c) controls pressurization and depressurization of the subsystem during mode transitions (i.e., start-ups and shutdowns).

Figure 7 is a functional schematic of one of the electrochemical cells which are installed electrically in series in the electrolysis module. Basically, a single cell consists of an electrode assembly, product gas cavities for H_2 and O_2, a feed water compartment and a coolant compartment for temperature control. The electrode assembly consists of a cathode, asbestos matrix and an anode. The N_2 purge line is activated during startup and pressurization, shutdown or in case of emergency. All fluid interfaces are manifolded with the respective ones of other cells in the module.

The overall static water feed concept operates as follows. Initially, the feed water compartment and the electrode assembly contain an aqueous solution of KOH electrolyte at an equal concentration. Both the H_2 and O_2 cavities are void of liquid. An equilibrium condition exists prior to start of electrolysis. When power is applied to the electrodes, water from the cell electrolyte is decomposed. As a result, the concentration of the cell electrolyte increases and its water vapor pressure decreases to a level below that of the feed compartment electrolyte. This water vapor pressure differential is a driving force causing water vapor to diffuse from the liquid gas interface within the water feed matrix, through the H_2 cavity and cathode electrode, into the cell electrolyte. This process establishes new steady-state conditions based on the water requirements for electrolysis.

As water evaporates from the feed water compartment it is statically replenished from the water feed tank to maintain a constant pressure within the feed compartment. Upon interruption of electrical power, water vapor will continue to diffuse across the H_2 compartment until the electrolyte concentration in the cell matrix is equal to that of the water feed compartment. At this point the original equilibrium condition is reestablished with the electrolyte having the initial charge concentration.

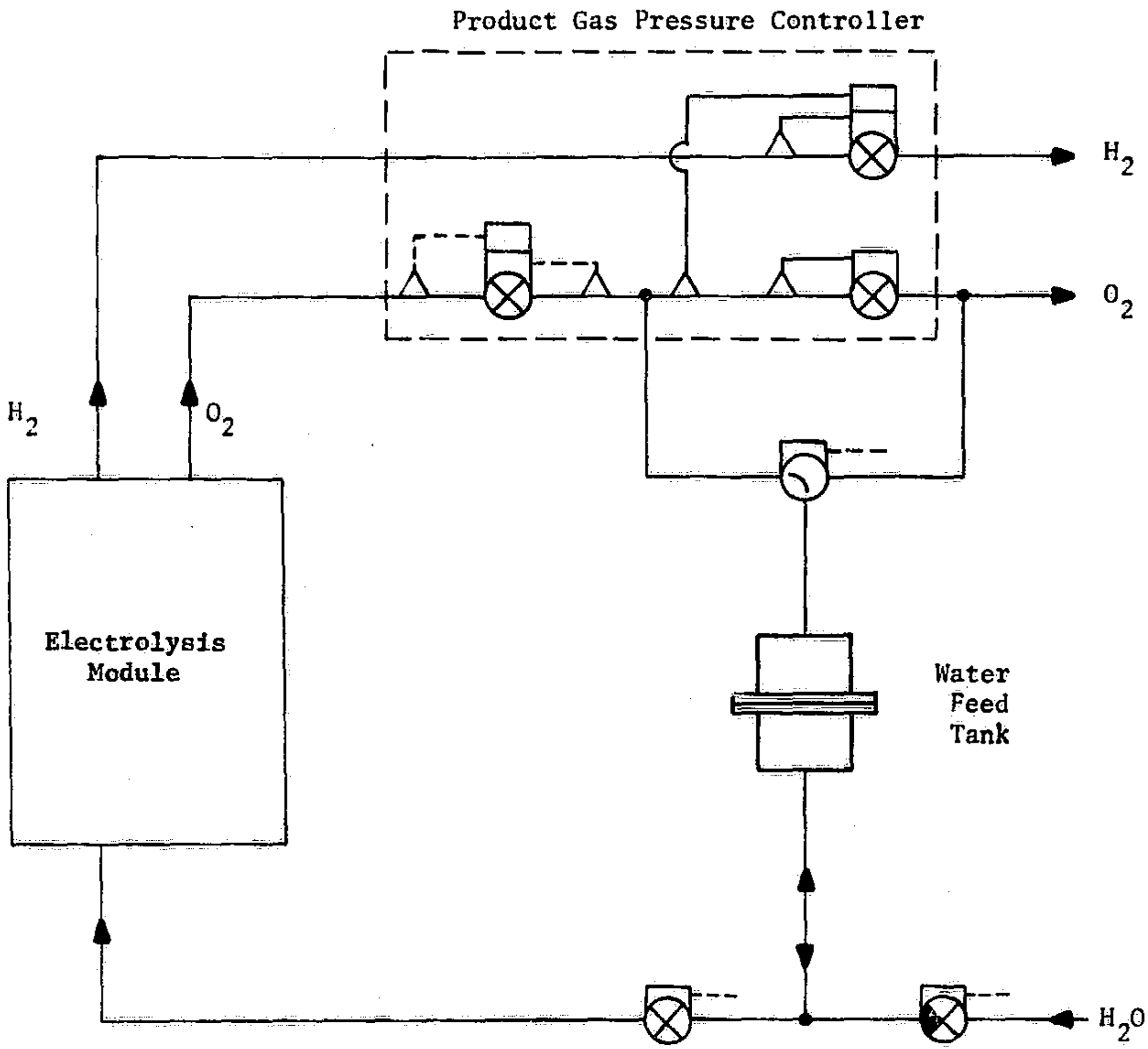


FIGURE 6 STATIC FEED WATER ELECTROLYSIS CONCEPT

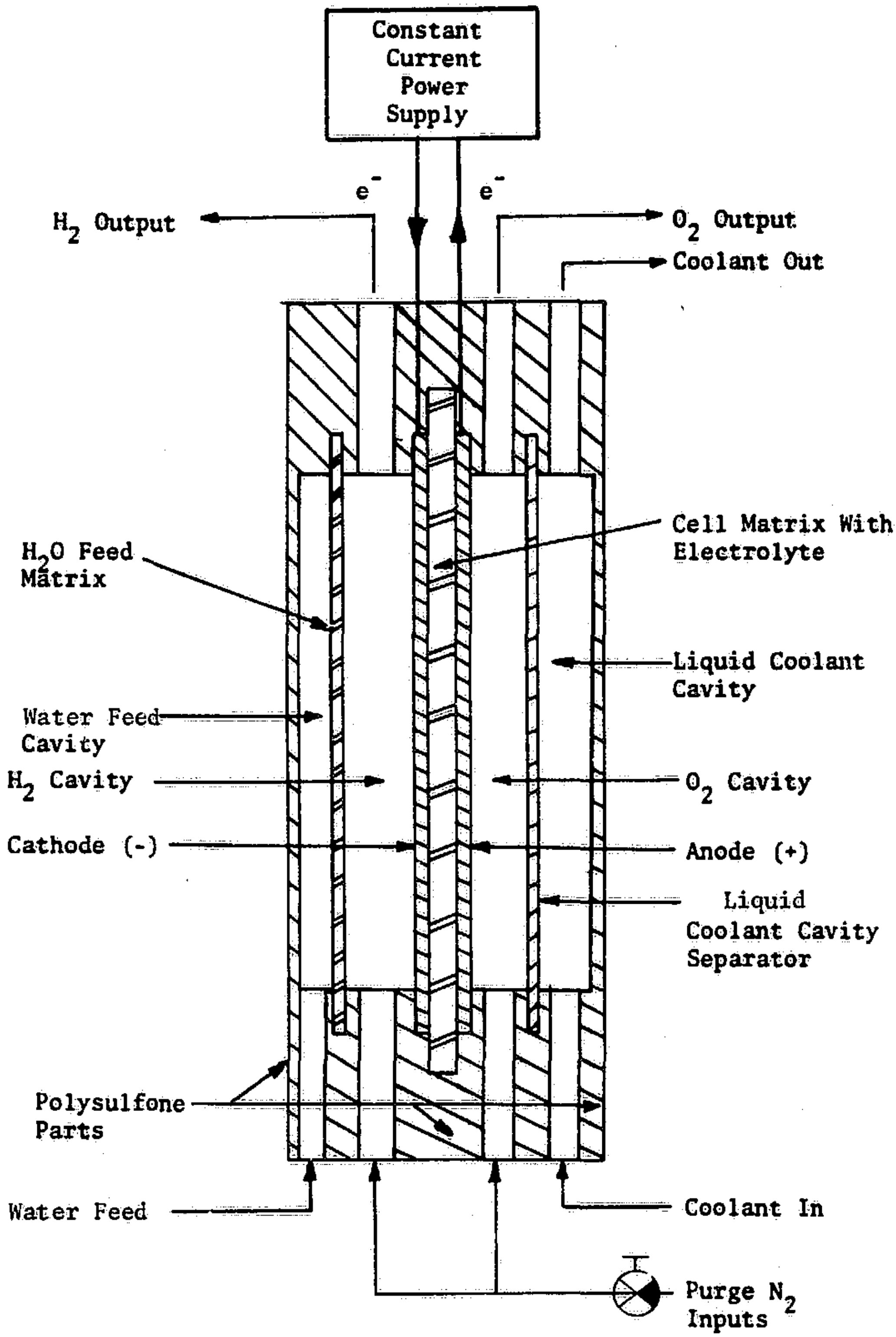


FIGURE 7 FUNCTIONAL SCHEMATIC OF AN SFWE CELL

Electrochemical Process. The electrochemical process of water electrolysis occurs within the cell's electrode assembly. The reactions occurring at the anode and cathode of the electrolysis cell with an alkaline electrolyte are:

Cathode

$$2e^- + 2H_2O = H_2 + 2OH^- \tag{1}$$

Anode

$$2OH^- = H_2O + 1/2\ O_2 + 2e^- \tag{2}$$

resulting in the overall reaction of

$$\text{electrical energy} + H_2O = H_2 + 1/2\ O_2 + \text{heat} \tag{3}$$

The flow rates of product gases are given by

$$G = IN\ \eta_c/(nF) \tag{4}$$

where G = product gas flow rates, g-moles/sec,
I = current, A
N = number of cells in series
η_c = current efficiency
n = number of electrons involved in reaction (1) or (2) to produce a molecule of a product gas
F = Faraday's constant, 96479 coulomb/equivalent

The current efficiency, η_c, may be defined as

$$\eta_c = W_a/W_t \tag{5}$$

where W_a = weight of desired product actually obtained and W_t = weight of desired product if current had been used solely to produce the desired product. Current efficiency is influenced by current density.

In analyzing electrochemical processes, energy efficiencies are also frequently calculated. Energy efficiency, η_e may be defined as follows:

$$\eta_e = E_t/E_a \tag{6}$$

where E_t = energy theoretically required, based on the decomposition voltage and on the amount of desired product actually obtained and E_a = actual energy input. The energy efficiency calculation may be based on the anode product or on the cathode product. If the current efficiencies for the anode and cathode are the same, energy efficiency may be calculated as:

$$\eta_e = \eta_c\ V_d/V_a \tag{7}$$

where V_d = decomposition voltage and V_a = actual cell voltage. The decomposition voltage is a function of operating temperature and pressure. The decomposition voltage of water at 298 K (77 F) and atmospheric pressure is 1.229 V.

Oxygen Generation Subsystem Descriptions

Design Specifications. The OGS was designed to deliver O_2 at a rate of 1.46 kg/d (3.22 lb/d) which included 0.83 kg/d (1.84 lb/d) O_2 for metabolic consumption and 0.63 kg/d (1.38 lb/d) for other requirements such as EDC consumption and cabin leakage makeup. Details of the OGS design specifications are presented in Table 2.

Schematic and Operation. The OGS schematic is shown in Figure 8. Basically, the OGS operates as described in the previous section. The water feed tank is periodically filled with water which is being treated by a deionizer. During normal operation the valve (13A), located downstream of the deionizer, is closed. Feed water is statically replenished to the electrolysis module as the water in the aqueous electrolyte solution is being electrolyzed.

A list of the OGS mechanical components is presented in Table 3. The 3-FPC is the key component which maintains the system pressure (water-feed tank pressure) and pressures of the product gases and their respective compartments in the module.

Temperature of the electrolysis module is kept uniform and constant by circulating water through the coolant cavities of the electrolysis cells. The module temperature can be varied for parametric testing by the use of electrical heaters, installed in the module endplates, and a liquid-to-air heat exchanger. A diverter valve in the coolant loop adjusts the water flow rate through the heat exchanger to maintain a constant module temperature.

Both the O_2 and H_2 compartments of each cell can be purged with N_2. The flow of the N_2 purge stream is regulated by orifices upstream of the module. The N_2 purging is not only a safety feature but also prevents module pressure from going subatmospheric due to the reaction of H_2 and O_2 after shutdown or isolation.

The nominal operating conditions of the OGS are presented in Table 4. The electrolysis module operated at a current density of 197 mA/cm^2 (183 ASF) to ensure that the OGS delivers O_2 at a rate equal to or greater than the specified production rate of 1.46 kg/d (3.22 lb/d). The module temperature and pressure were set at 339 K (150 F) and 1,068 kPa (155 psia), respectively. The initial module charge concentration of KOH was 25% by weight.

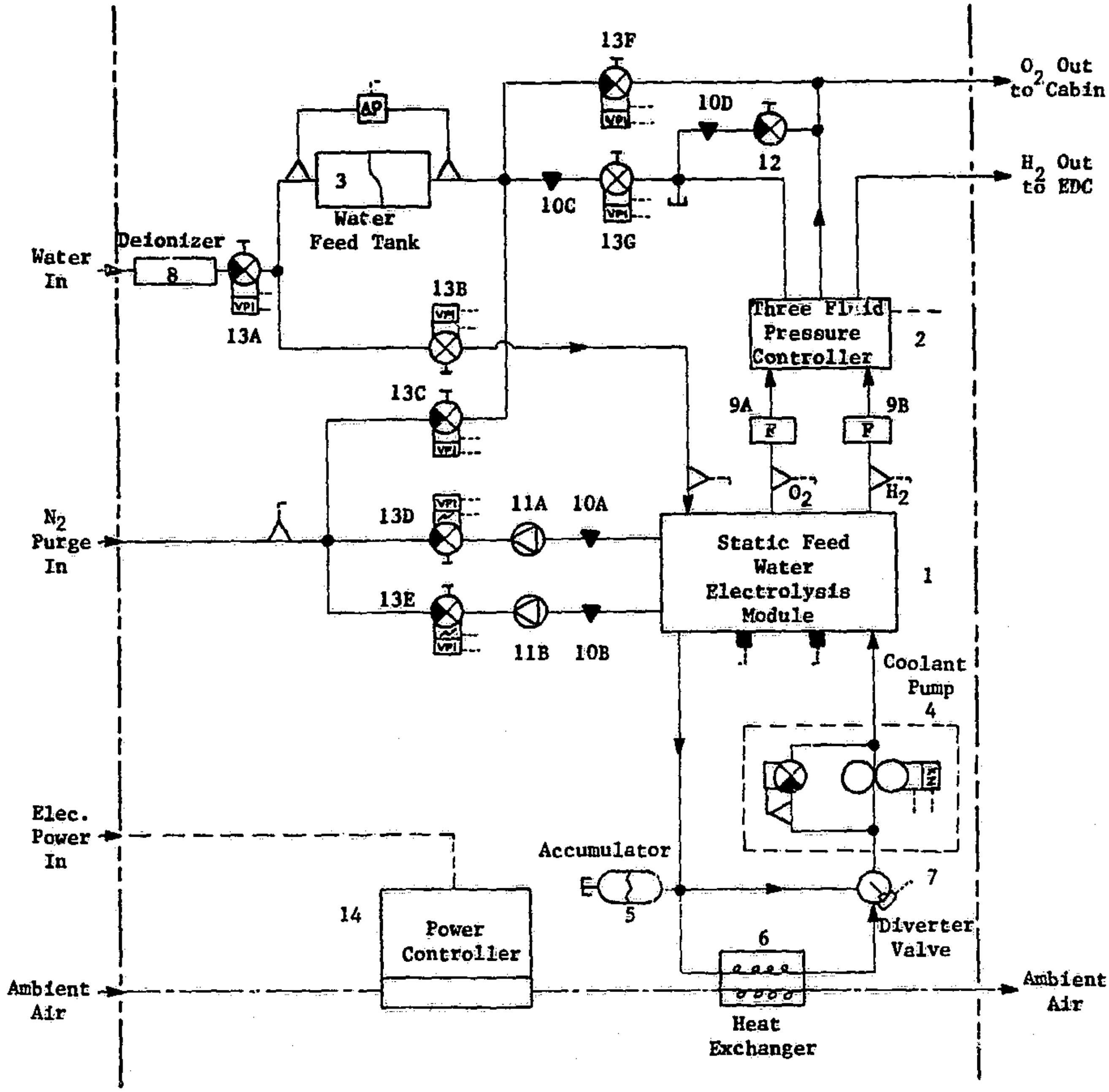
Hardware Descriptions. Unique components of the OGS design are the electrochemical module and the 3-FPC. The remaining ancillary components were either commercially available or other LSI state-of-the-art hardware.

The design of the SFWE Module (SFWEM) was based on the single-cell components shown in Figure 9. Twelve electrolysis cells were assembled using an endplate-to-endplate concept to minimize interconnecting plumbing, as shown in Figure 10. The active electrode area of a single cell is 92.9 cm^2 (0.1 ft^2). The electrolysis cells were interconnected in series electrically. All fluid connections were made in parallel. Detailed descriptions of the design have been presented in a previous report.[2]

TABLE 2 OGS DESIGN SPECIFICATIONS

Crew Size	1
O_2 Generation Rate[a], kg/d (lb/d)	1.46 (3.22)
H_2 Generation Rate, kg/d (lb/d)	0.18 (0.41)
Water Supply	
Pressure, kPa (psia)	207 (30)
Temperature, K (F)	277 to 300 (40 to 80)
Cooling Air	
Total Pressure, kPa (psia)	101 (14.7)
Temperature, K (F)	294 (70)
Purge Gas Supply	
Type	N_2
Pressure, kPa (psia)	965 (140)
Electrical Power, V	
DC	24
AC	115/200 (60 Hz, 1 and 3 Phase)
Gravity, g	0 to 1
Duty Cycle	Continuous

(a) Includes 0.83 kg/d (1.84 lb/d) O_2 for metabolic consumption and 0.63 kg/d (1.38 lb/d) for other requirements such as cabin leakage makeup and EDC consumption.



Note: Numbers shown adjacent to components refer to part numbers used in Table 3.

FIGURE 8 OGS FLOW SCHEMATIC

TABLE 3 OGS MECHANICAL COMPONENT LIST

Part No.	Component	Number Required	Identification Code[a]
1	Electrochemical Module	1	WE1/DM1
2	Three-Fluid Pressure Controller	1	PC1
3	Water Storage Tank	1	WST1
4	Coolant Pump	1	M3
5	Coolant Accumulator	1	WA2
6	Liquid/Air Heat Exchanger	1	HX3
7	Coolant Flow Diverter Valve	1	V22
8	Feed Water Deionizer	1	WD1
9	Product Gas Filter	2	AF3, 4
10	Orifice	4	R4, 5, 7, 8
11	Check Valve	2	CV1, 2
12	Hand Valve	1	MV10
13	Solenoid Valve	7	V9, 10, 11, 12 16, 17, 18
14	Power Controller	1	-

(a) As used in ARX-1 System Schematic, LSI-J-1407, (Appendix 1).

TABLE 4 OGS NOMINAL OPERATING CONDITIONS

Current, A	18.3
Current Density, mA/cm^2 (ASF)	197 (183)
Average Cell Voltage, V	1.5[(a)]
Module Temperature, K (F)	339 (150)
Pressures	
• H_2O Feed, kPa (psia)	1069 (155)
• H_2-to-H_2O Differential, kPa (psid)	17.2 (2.5)
• O_2-to-H_2O Differential, kPa (psid)	27.6 (4.0)
• N_2 Purge, kPa (psia)	965 (140)
Flow Rates, kg/d (lb/d)	
• H_2O Feed	1.75 (3.86)
• O_2 Product	1.55 (3.43)
• H_2 Product	0.20 (0.43)
Electrolyte Charge Concentration, wt %	25% KOH

(a) With super electrodes; 1.7 V with advanced electrodes.

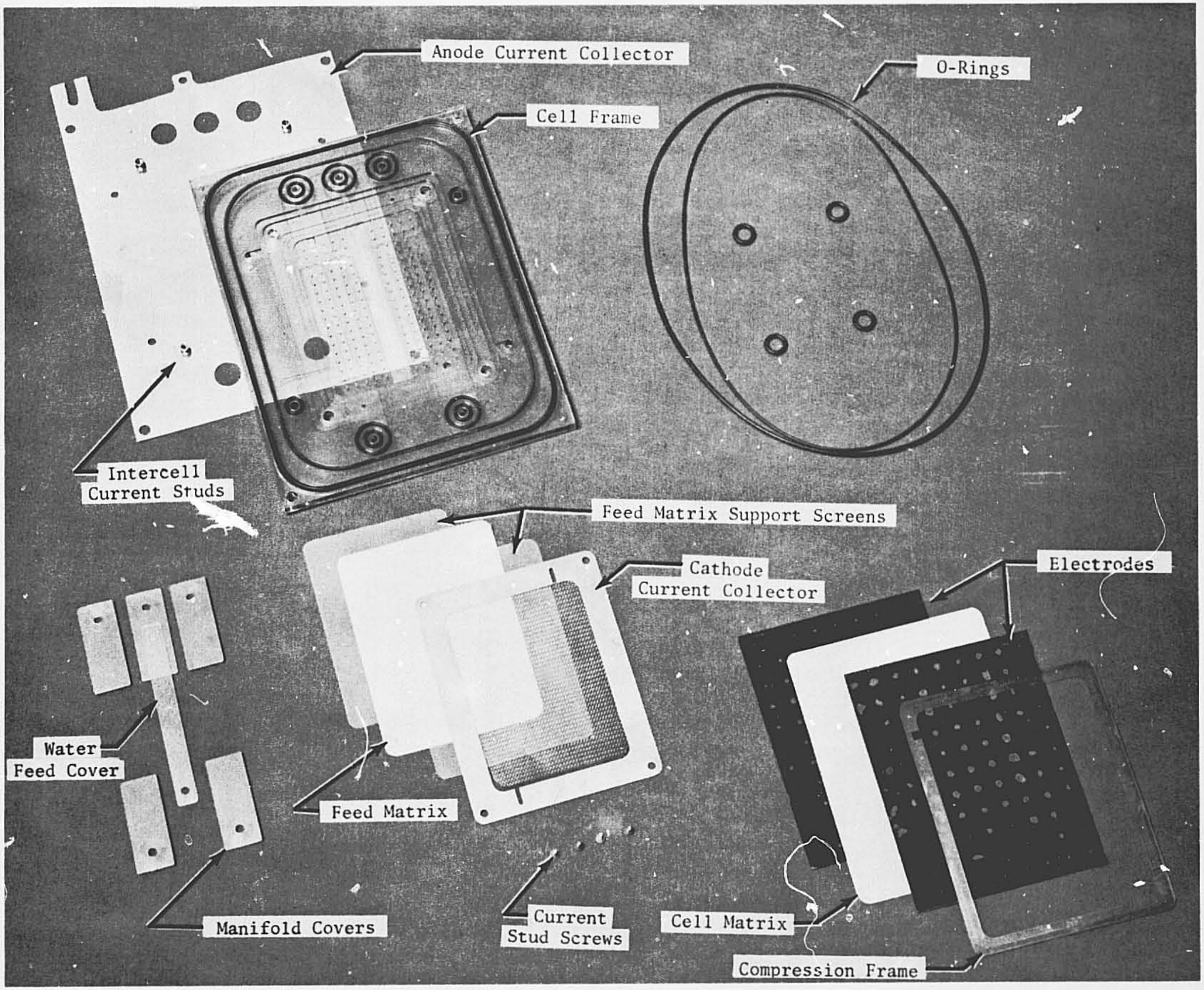


FIGURE 9 SINGLE-CELL PARTS

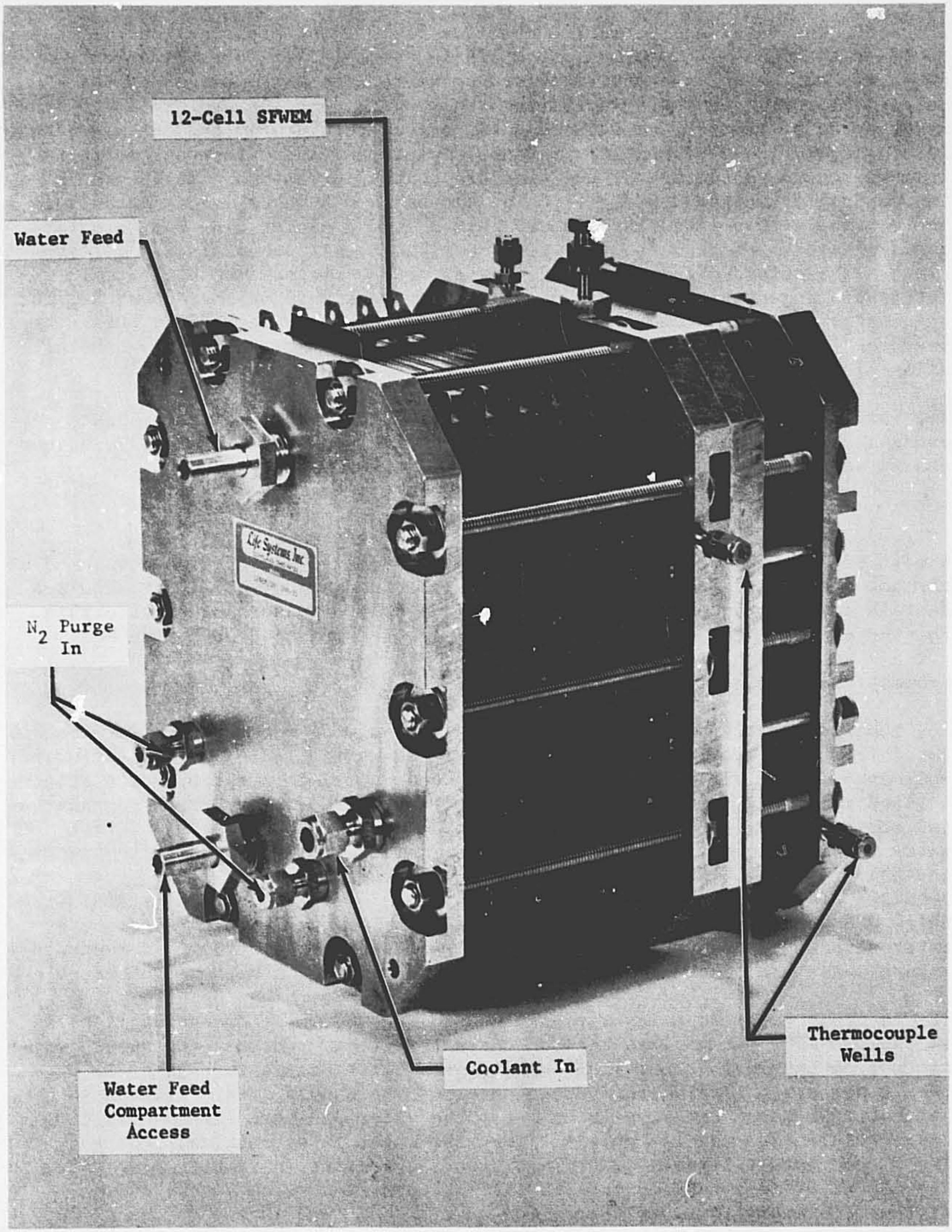


FIGURE 10 STATIC FEED WATER ELECTROLYSIS MODULE

The 3-FPC was developed to meet the unique fluidic and pressure control requirements of the OGS. It combined, in a single assembly, the sensors and actuators necessary to control and monitor fluid pressure levels and differentials during all operating modes including steady-state, startup and shutdown. The major parts of the 3-FPC are three motor-driven regulators, one total pressure level sensor, two differential pressure sensors and three feedback position indicators. A photograph of the pressure controller is shown in Figure 11. The controller weighs 3.65 kg (8.0 lb) and has a volume of 1.58 cm^3 (96.3 in^3). The controller has five fluid interfaces: H_2 and O_2 inlets, H_2 and O_2 outlets and a pressure reference to the water feed tank. All other fluid interconnections are manifolded internally and sealed with O-rings. The electrical interface is made with a standard connector. Sensor signals are sent to, and actuator signals are received from, the subsystem instrumentation. With these features, the pressure controller is ideally suited for closed-loop control using microprocessor- or minicomputer-based instrumentation.

The ancillary components of the OGS consisted of solenoid valves, a heat exchanger, a coolant pump and bladder-type tanks and accumulators. No unique design was needed.

Water Handling Subsystem

Within air revitalization subsystems liquid water is generated and consumed at various locations. The OGS is the principal consumer of water. It requires certain components to provide an automatic supply of water for electrolysis. For the ARX-1, these components have been grouped and treated as the WHS.

Schematic and Operation

The function of the WHS is to ensure that a supply of water exists for the OGS water feed tank. A schematic of the WHS is shown in Figure 12. The principal component in the WHS is a pressure referenced water storage tank which at prescribed intervals fills the OGS water feed tank. The water comes from one of two sources: one internal, the other external to the ARX-1. The internal water source combines the water collected from the S-CRS condenser/separator and that from the CHCS. These two sources normally supply all the water required by the OGS. If, however, the internal water collection is diminished below OGS requirements, additional or makeup water can be supplied from an external source. Conversely, if the internal supplies exceed OGS demand, the excess water can be dumped to external storage through a backpressure regulator.

The internal water supplies normally exceed the OGS water demand as is shown in Table 5 which summarizes the WHS characteristics. Whether the supply water comes from internal or external supplies, it first passes through a filter, then a deiodinator/deionizer before entering the supply tank. Filling is automatic whenever the pump is on until the water pressure exceeds the dump backpressure (303 kPa (44 psia)). Then the water is automatically dumped. The N_2 pressure reference (200 kPa (29 psia)) assists in transferring water to the OGS water feed tank during its filling operation which occurs during startup and every 12 hours thereafter.

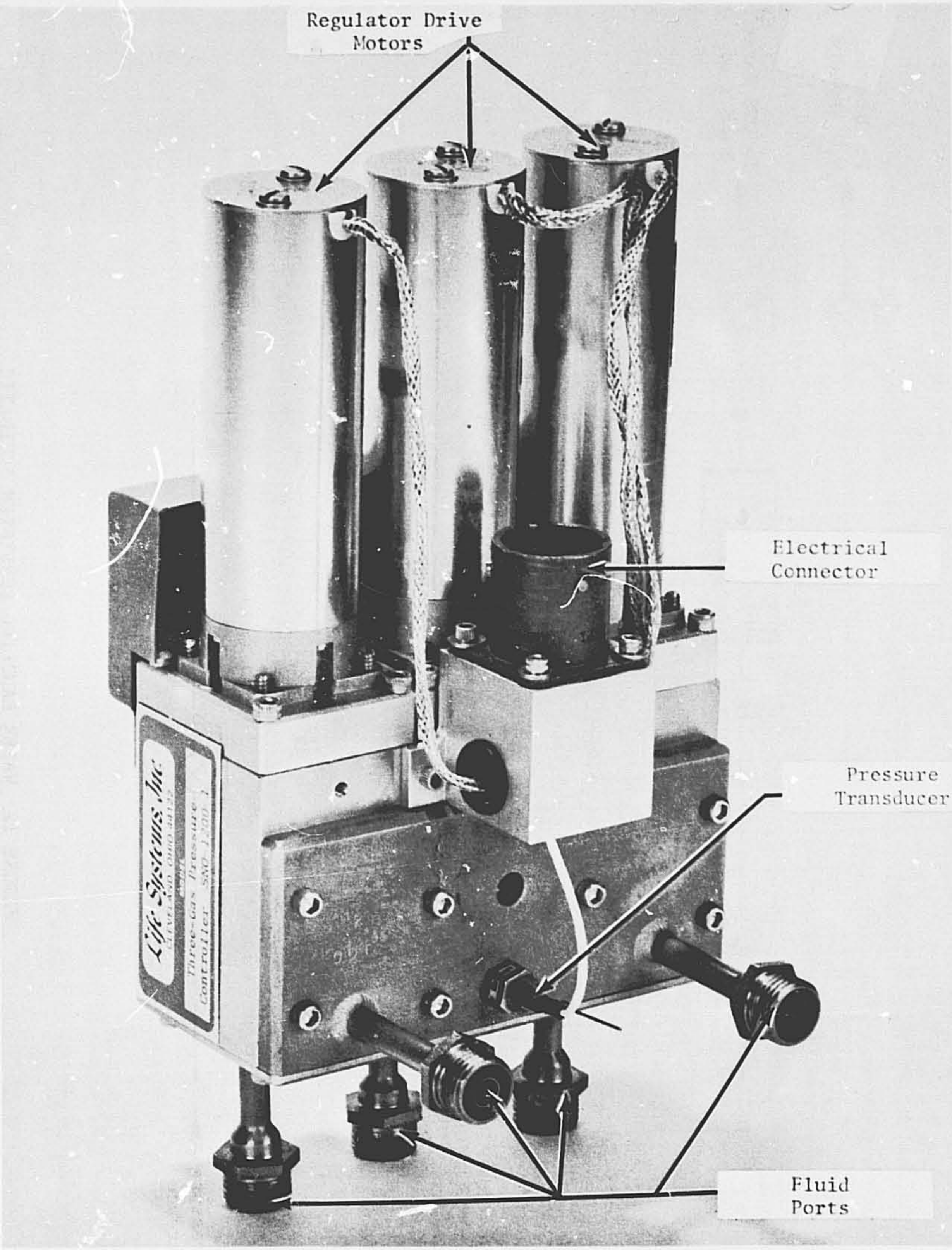


FIGURE 11 THREE-FLUID PRESSURE CONTROLLER

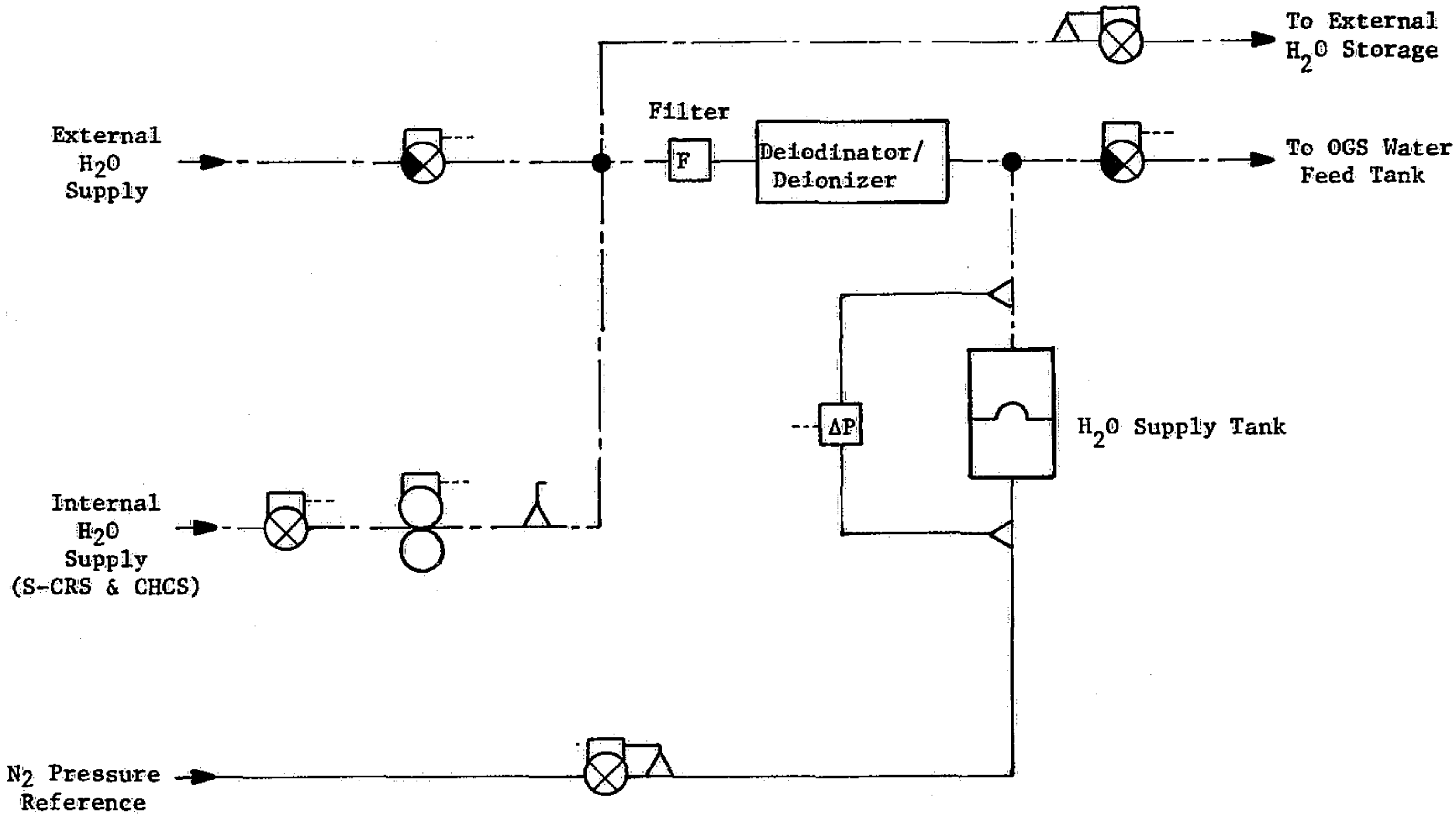


FIGURE 12 WATER HANDLING SUBSYSTEM SCHEMATIC

TABLE 5 WATER HANDLING SUBSYSTEM CHARACTERISTICS

Nominal Water Flow Rates, kg/d (lb/d)	
From S-CRS	0.41 (0.91)
From CHCS	1.80 (3.96)
To OGS	1.75 (3.86)
To External Storage	0.46 (1.01)
Water Supply Tank	
Capacity, l (in^3)	2.46 (150)
Reference Pressure, kPa (psia)	200 (29)
Emptying Cycle, h	12
Filling Cycle	
From internal	When Pump is On
From external	On Demand
External Supply Pressure, kPa (psia)	240 (35)
Dump Pressure to External Storage, kPa (psia)	303 (44)

Hardware Description

The hardware components of the WHS consist of valves, a pump, a deiodinator/deionizer and a water supply tank. The valves and pump are standard off-the-shelf components. The deiodinator/deionizer, shown in Figure 13, was developed under this program. The 2.4 kg (5.3 lb) unit contains both a charcoal and an ion-exchange resin bed for removing iodine ions and dissolved CO_2 from the feed water of the OGS. The charcoal bed also serves as the filter designated in Figure 12.

The water supply tank is shown in Figure 14. The tank, consisting of two stainless steel halves separated by a flexible diaphragm, has a dry weight of 3.7 kg (8.2 lb) and holds 2.46 l (150 in^3) of water.

Control and Monitor Instrumentation

The C/M I provides for automatic control and monitoring of the ARX-1 operation. Through a combination of minicomputer, analog circuitry hardware and assembly language software, all functions of mode and mode transition control, automatic shutdown, monitoring of system parameters and TSA interfacing were provided. The following describes details of the C/M I design and operation with emphasis on the portions which relate to the OGS.

Power Sharing Concept

The electrical power which the EDC module (EDCM) generates has historically been converted to heat and removed from the subsystem as a waste product. Life Systems, Inc. developed a concept for using the EDCM power directly by supplying this power to the OGS when the two are operated as part of an integrated system as in the ARX-1.[11,12] Using this technique, the EDCM power can be directly subtracted from the power required to operate the SFWEM in the OGS. The remaining power required to operate the SFWEM is then obtained from the input power as shown in Figure 15. The power controller contains the circuits needed to automatically allow the utilization of EDCM power and to convert the input power to the voltage and current levels required by the SFWEM. All of the EDCM-generated power is utilized. It is not necessary to send it through a power conversion circuit before it is supplied to the SFWEM. For the ARX-1, approximately 10% of the SFWEM power was supplied by the EDCM.

Operating Modes and Mode Transitions

The C/M I provides for five operating modes: (1) Shutdown, (2) Normal, (3) Purge, (4) Standby and (5) Unpowered. These operating modes and the allowable mode transitions are shown in Figure 16. In the Normal Mode the system generates O_2, removes and reduces CO_2, controls cabin humidity and distributes or stores water, as required. In the Shutdown Mode these functions are inoperative but the system is powered and all sensors are working. During Purge, all H_2-carrying lines throughout the system are being purged with N_2. In the Standby Mode the system is powered and maintained at operating temperatures and pressures; however, actual conversion processes are not taking place.

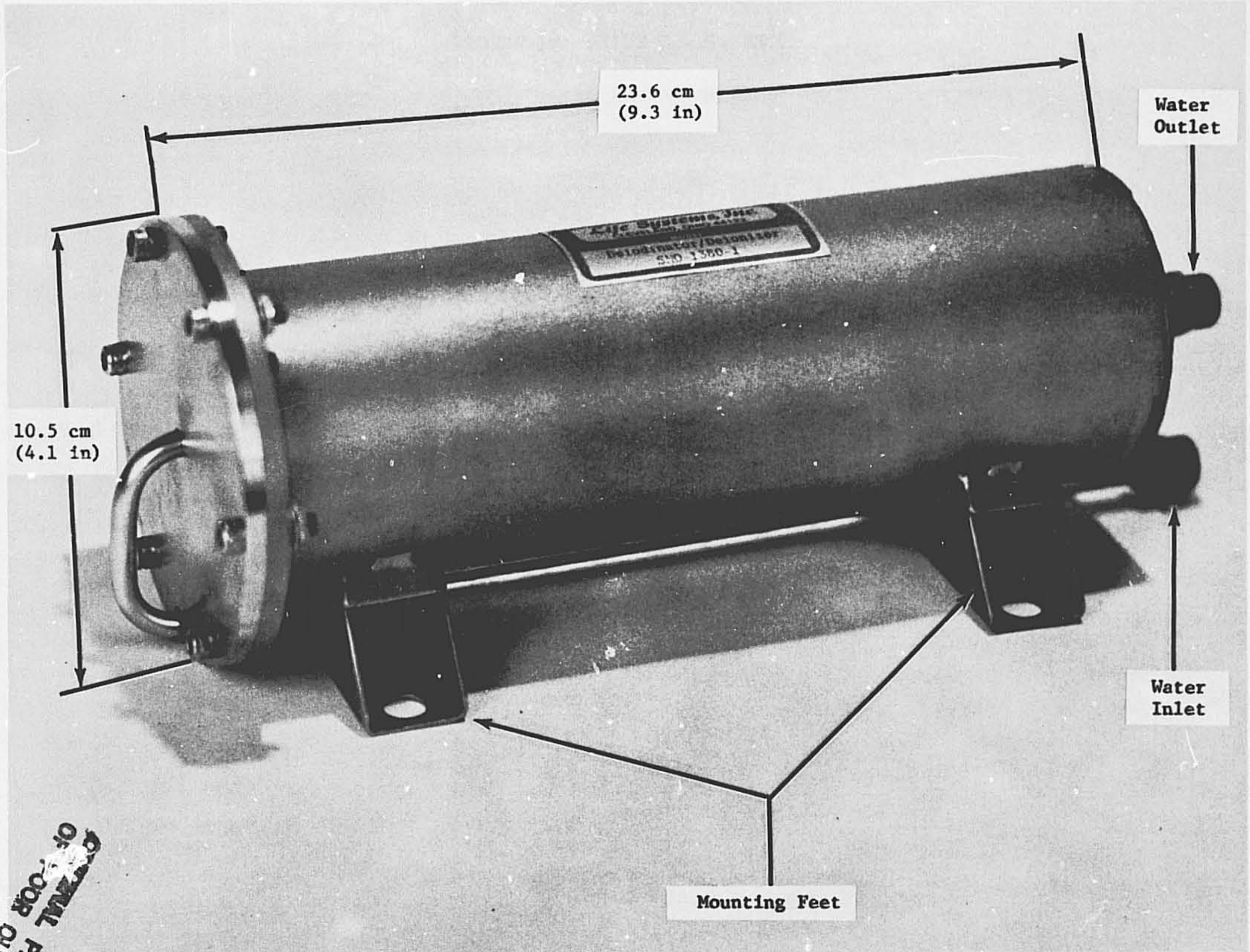


FIGURE 13 DEIODINATOR/DEIONIZER

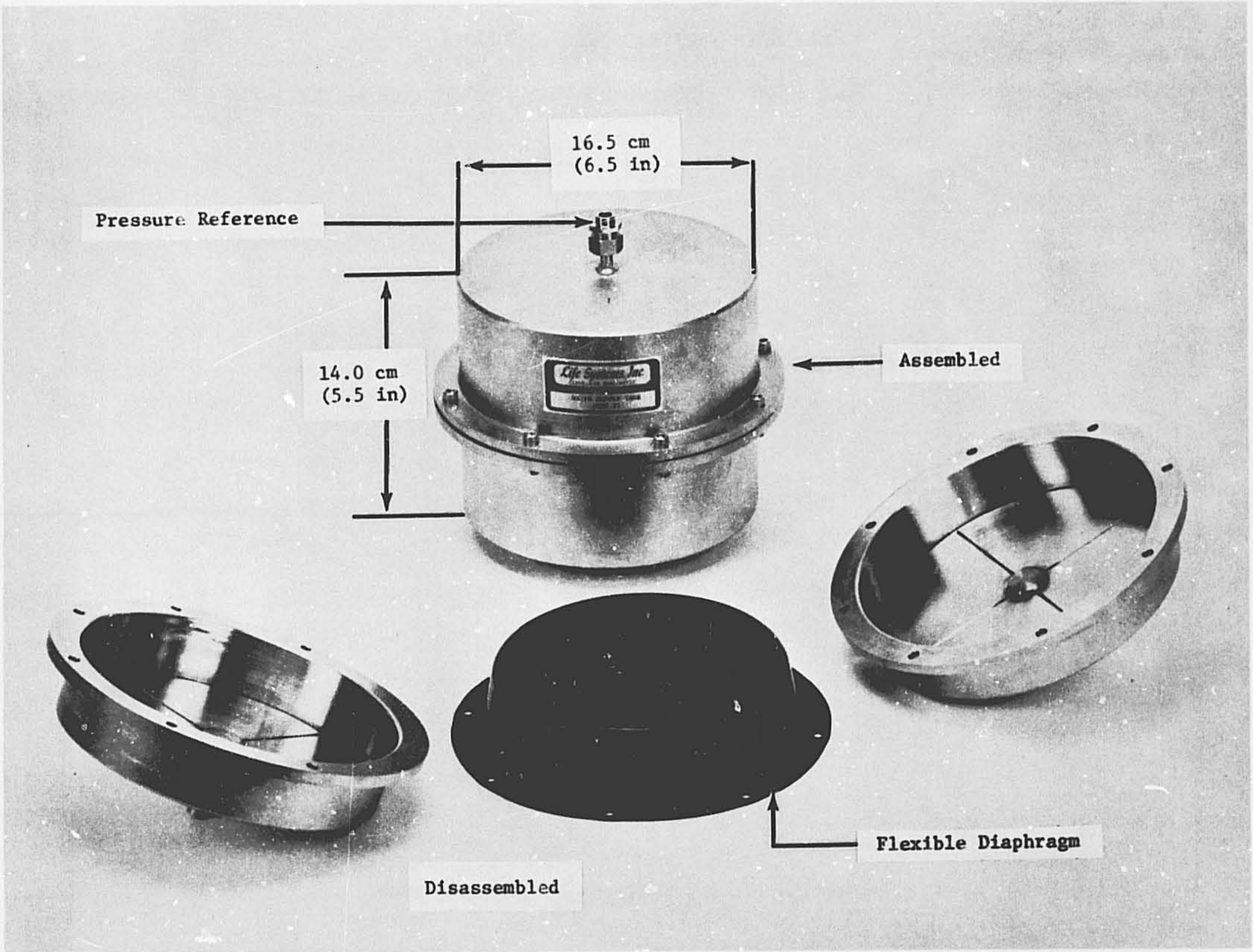


FIGURE 14 WATER SUPPLY TANK

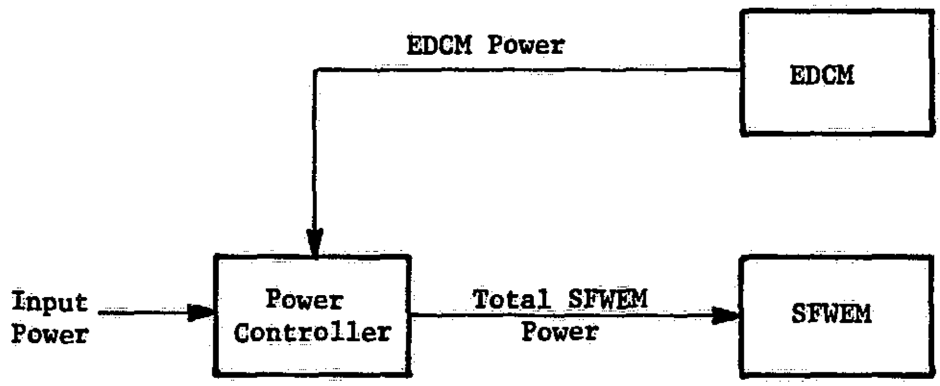


FIGURE 15 POWER CONTROLLER BLOCK DIAGRAM

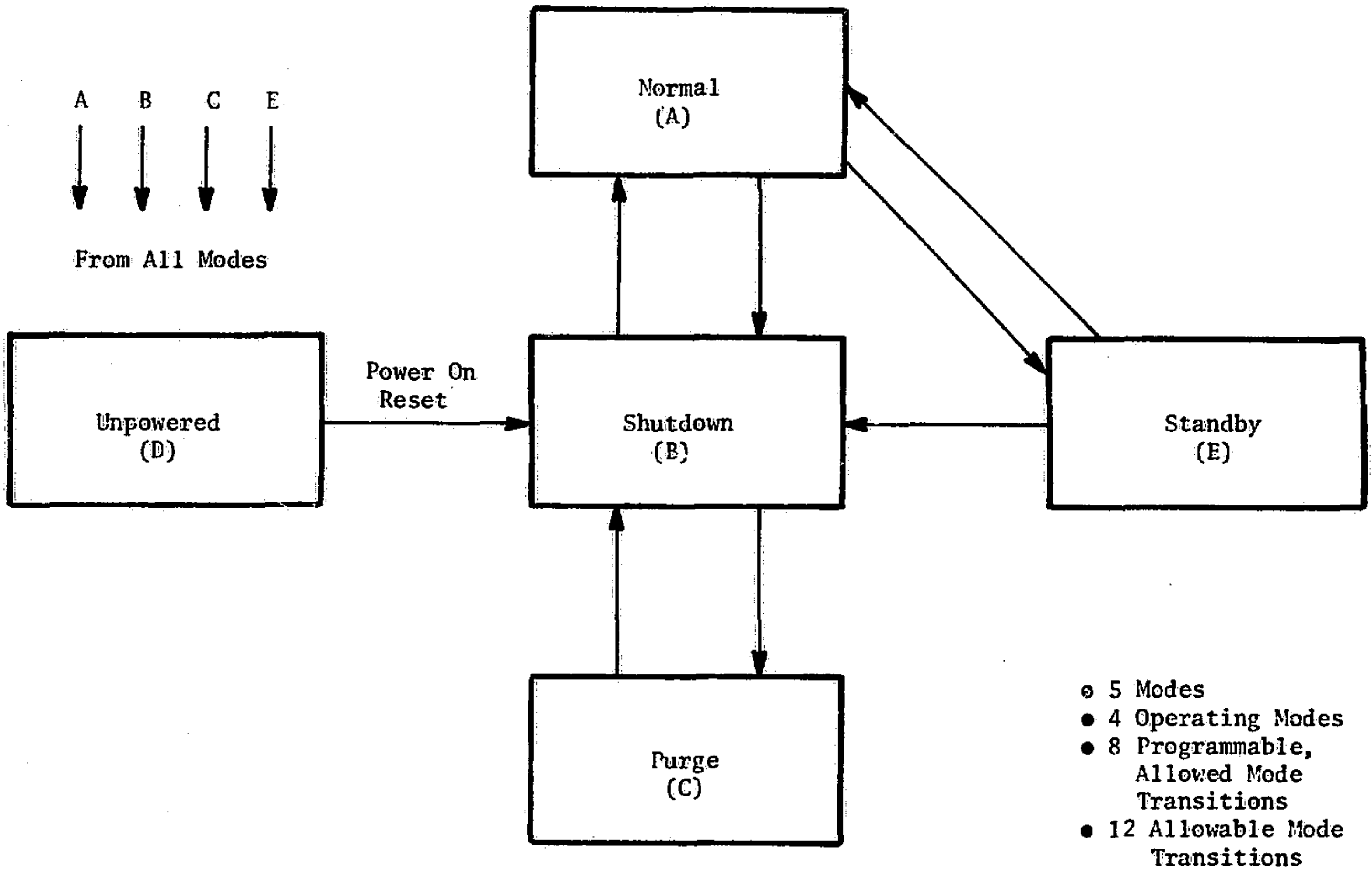


FIGURE 16 OPERATING MODES AND ALLOWABLE MODE TRANSITIONS

Finally, in the Unpowered Mode, no electrical power is applied to the system and there are no fluid flows. Further details of the mode definitions are presented in Appendix 2.

System Control and Monitoring

There are 16 controls needed to operate the ARX-1. These include controls for EDCM temperature and current, S-CRS temperature, CHCS temperature, water accumulator fill and/or empty, OGS temperature, pressure and current, and N_2 Generation Module (NGM) pressure and temperature. The controls for the OGS and WHS are highlighted in Table 6.

Sensors are required to interface with the C/M I to provide for control and monitoring of subsystem parameters and performance. Over 100 sensors are implemented in the ARX-1. These monitor flows, pressures, temperatures, currents, voltages, liquid levels, combustible gas presence and valve positions. Fifty-five monitors, identified in Table 7, are specifically associated with the OGS and WHS. In addition, Table 8 identifies subsystem parameter conditions which will call for an automatic, controlled shutdown of the ARX-1. The shutdown conditions can be easily modified by the operator through an operator/system interface.

Operator/System Interface

Figure 17 shows the operator/system interface panel of the C/M I through which the operator can communicate with the system. The panel is subdivided into three major areas: System Status, Operator Commands and System Control.

The overall system status is provided in the upper left-hand portion of the panel. The status summary is given as Normal, Caution, Warning or Alarm and is determined by the worst case condition for any critical parameter. A reset button is provided to clear the status summary and reset the subsystem monitoring functions. Messages and information concerning the system are displayed on a Cathode-Ray Tube (CRT) located below the status summary indicators. In addition, the CRT displays fault diagnostic messages, present status and values of selected sensors, input/output data, elapsed times and communications between the system and an operator.

The operator commands section in the lower left-hand corner provides the capability of the operator to communicate with the system. Capability exists for entering data, examining current values, updating scale factors, modifying setpoints or allowable ranges and control of the CRT display.

Manual initiation of the four operating modes (Normal, Shutdown, Purge and Standby) is provided in the upper right-hand corner of the panel. The controls automatically prevent the operator from initiating an illegal mode transition (e.g., Normal to Purge). The subsystem will not respond to an illegal mode transition command. Accidental mode initiation is prevented by providing a mode change permit button which must be simultaneously depressed with the desired mode button.

TABLE 6 OGS AND WHS CONTROLS DEFINITION

Parameter Controlled	Control Description	Controlled Actuator
SFWEM Temperature	Regulates liquid coolant flow through bypass heat exchanger to maintain desired coolant temperature	Coolant Diverter Valve
SFWEM Pressure	Controls OGS system pressure to setpoint, H_2 pressure at desired ΔP above setpoint and O_2 pressure at desired ΔP above H_2 pressure	Three-Fluid Pressure Controller
SFWEM Current	Controls current flow to SFWEM cells to regulate production of O_2 and H_2	Power Supply/ Power Sharing Circuitry
Dehumidifier Module (DM) Current	Maintains DM current at desired setpoint level	Power Supply/ Conditioning
DM Voltage	Sets a specified voltage for software control. Interfaces with DM Current Control	Power Supply/ Conditioning
Water Feed Tank Fill	Fills SFWEM Feed Tank every 12 hours or when Feed Tank ΔP is greater than fixed level	Miscellaneous Valves/Sequences
Water Storage Tank Fill	Maintains Storage Tank filled. Fills tank when tank ΔP is greater than fixed level	External Water Source Isolation Valve

TABLE 7 SENSOR LIST

Sensor Location	Parameter Monitored	No. Sensors
Oxygen Generation Subsystem	SFWEM Temperature	2
	DM Temperature	2
	Feed Water Inlet Pressure	1
	SFWEM Current	1
	SFWEM Cell Voltage	12
	DM Current	1
	DM Cell Voltage	3
	H_2, O_2 Outlet Pressure	2
	System Regulator Pressure	1
	H_2, O_2 ΔP	2
	N_2 Purge Supply Pressure	1
	Combustible Gas Contamination in O_2	3
	Valve Position Indicators	11
Water Handling Subsystem	Accumulator Pressure	1
	Pump Outlet Pressure	1
	Deionizer ΔP	1
	SFWEM Feed Water Tank ΔP	1
	Water Supply Tank ΔP	1
	Feed Water Conductivity	1
	Accumulator Level	2
	Valve Position Indicator	5

TABLE 8 PARAMETERS MONITORED FOR AUTOMATIC SHUTDOWN

Parameter	Shutdown Condition
Low Cell Voltage, V	1.45
High Cell Voltage, V	1.90
Low Current, A	15.0
High Current, A	30.0
High Temperature, K (F)	356 (180)
Low Feed Water Filter ΔP, kPa (psid)	-21 (-3.0)
High Feed Water Filter ΔP, kPa (psid)	21 (3.0)
Low Feed Water Tank ΔP, kPa (psid)	-14 (-2.1)
High Feed Water Tank ΔP, kPa (psid)	14 (2.1)
Low System Pressure, kPa (psia)	760 (110)
High System Pressure, kPa (psia)	1170 (170)
Low N_2 Supply Pressure, kPa (psia)	790 (115)
High N_2 Supply Pressure, kPa (psia)	1070 (155)
Low H_2-to-Water ΔP, kPa (psid)	-21 (-3)
High H_2-to-Water ΔP, kPa (psid)	69 (10)
Low O_2-to-Water ΔP, kPa (psid)	-6.9 (-1)
High O_2-to-Water ΔP, kPa (psid)	69 (10)
Low Water Supply Tank ΔP, kPa (psid)	41 (-6)
High Water Supply Tank ΔP, kPa (psid)	14 (2)

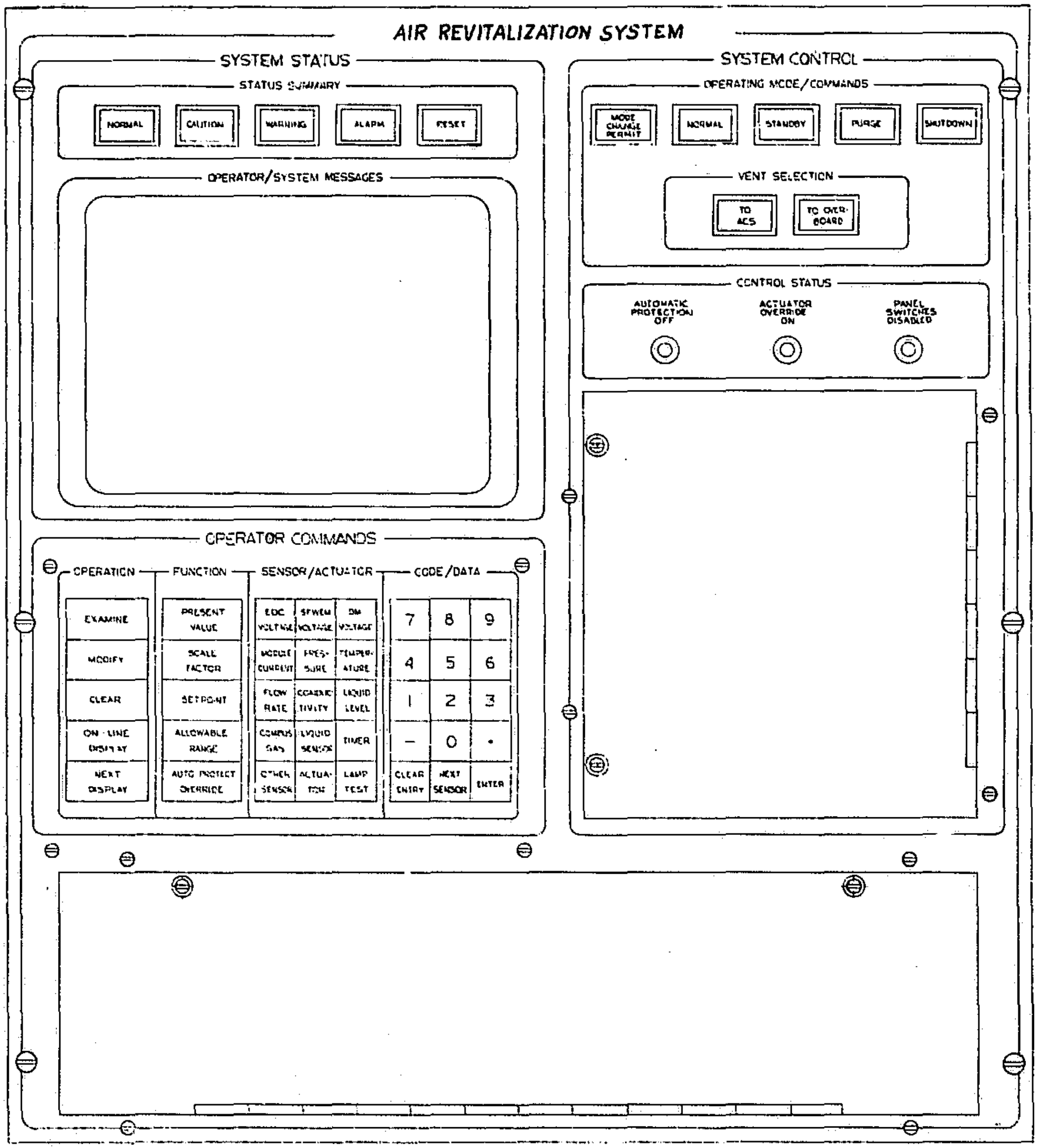


FIGURE 17 ONE-PERSON AIR REVITALIZATION SYSTEM OPERATOR/SYSTEM INTERFACE PANEL

The control status is located directly below the operating mode/commands section. Two lights are provided to indicate whether one of the automatic protection overrides or an actuator override has been activated. A light is also provided to indicate when the panel switches have been disabled, a condition used to prevent unauthorized personnel to activate any button.

Manual controls, designed primarily for use during system debug or off-design operation, are provided behind an access panel located immediately below the operator commands and system control sections. Overrides are provided for all actuators in the form of toggle switches. The actuator overrides must be placed in an automatic position for the system to operate normally. Also, manual adjustments are provided for adjusting certain setpoints such as SFWEM current. The access panel is normally closed to prevent accidental actuations.

Software

The ARX-1 software is organized into 70 different software packages or modules. They are divided into system definition and data base, front panel service, real-time executive, input/output, control/monitor, operating mode control and intermode transition functions. Of the total, the OGS and WHS require 15 of the modules exclusively and share the majority of the remainder.

TEST SUPPORT ACCESSORIES

Test Support Accessories were developed to support the test program of the ARX-1. The laboratory breadboard module test stand developed under a previous program (Contract NAS2-7470) was used for the SFWEM endurance testing.

One-Person Air Revitalization System

A block diagram of the ARS TSA is shown in Figure 18. Some of the TSA hardware was developed or refurbished as part of this program; some was provided from prior programs and modified. This hardware included part or all of the Fluid Supply Unit, the Air Supply Unit and its control, the Coolant Supply Unit, a N_2H_4 Refill Facility, the Vent/Vacuum Source, the Data Acquisition Unit and the Parametric Data Display. Test Support Accessories that were needed specifically for the OGS testing included the N_2 purge supply and a water source with liquid level monitoring. Also, raw DC power was supplied to the C/M I which further conditioned the power to operate the OGS and, in conjunction with the power-sharing concept, the EDC.

A major portion of the TSA activities was involved with the development of the parametric data display unit. The unit, packaged in a separate cabinet, is shown in Figure 19. It services all of the functions of the ARX-1. Specifically, it contains displays for temperatures, cell voltages and currents, flows and pressures. Also shown in the lower portion of the cabinet are power supplies required for operation of the parametric data display unit and the ARX-1.

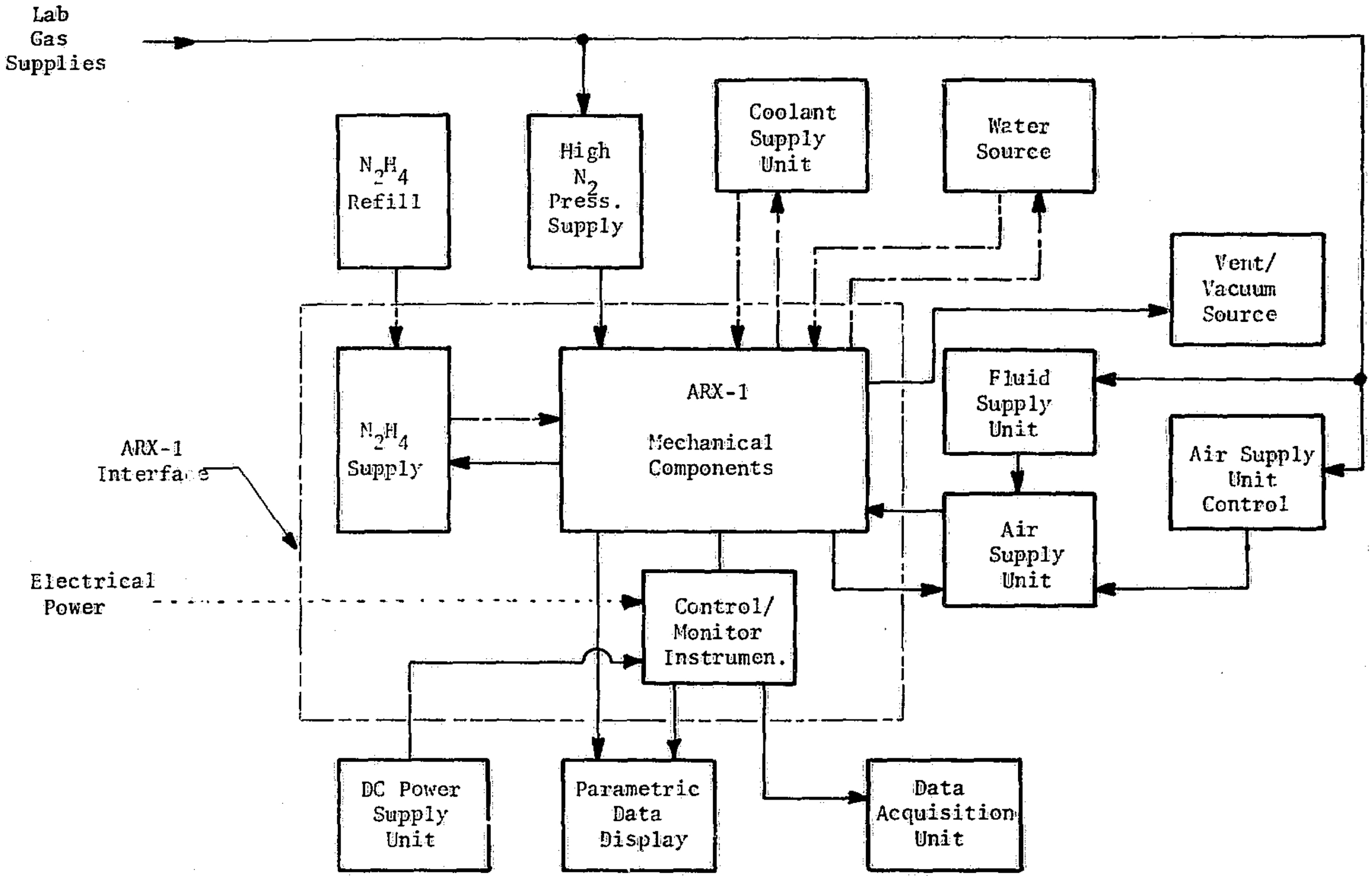


FIGURE 18 ONE-PERSON AIR REVITALIZATION SYSTEM TSA BLOCK DIAGRAM

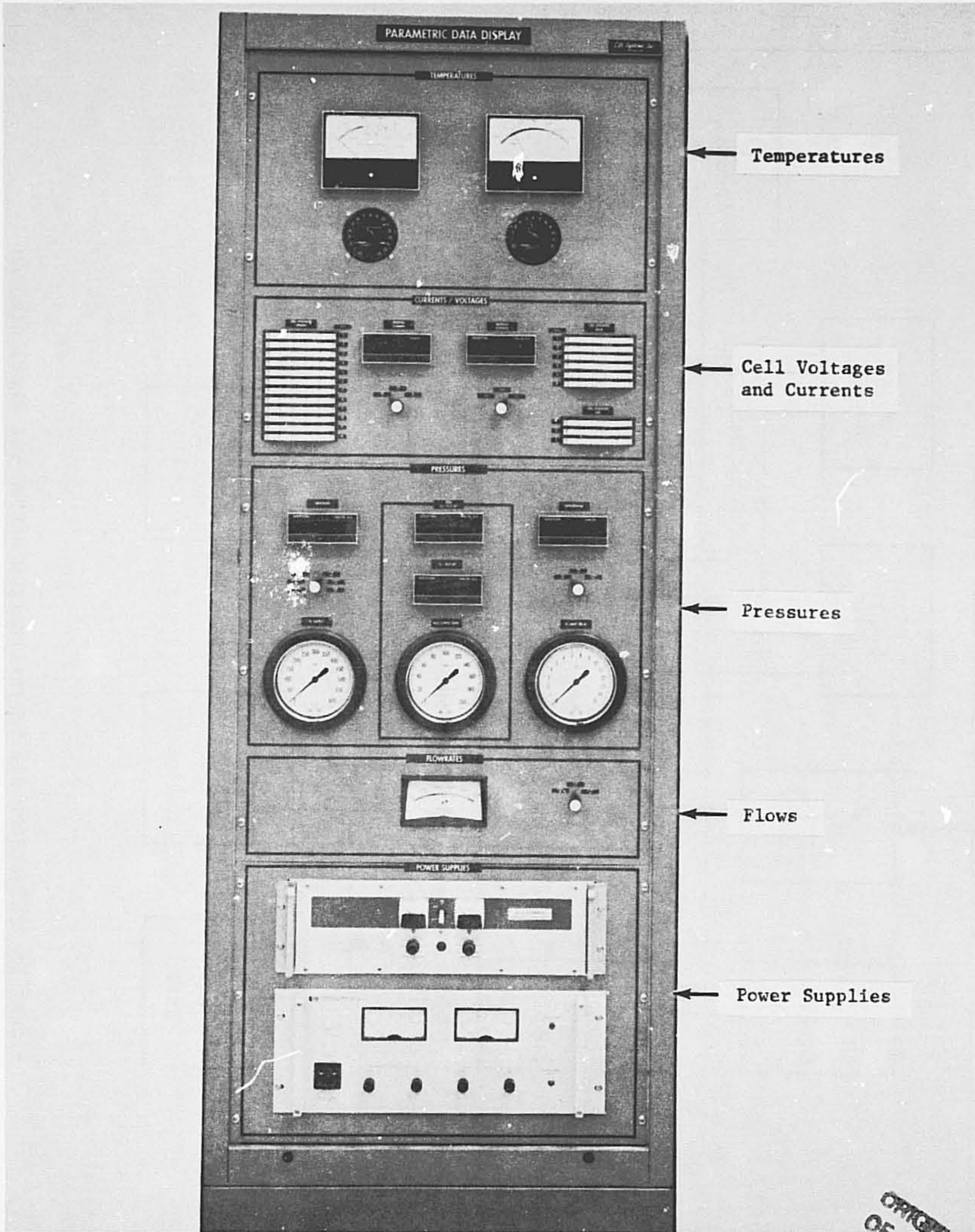


FIGURE 19 ONE-PERSON AIR REVITALIZATION SYSTEM
PARAMETRIC DATA DISPLAY CABINET

Laboratory Breadboard Module Test Stand

Two 12-cell electrolysis modules were tested in the laboratory breadboard test stand shown in Figure 20. Detailed descriptions of the test stand can be found elsewhere.[2,4]

The primary purpose of the test stand was to allow for bench-top testing of the SFWEM in order to advance the SFWE and module technologies. The basic configuration of the test stand schematic is similar to that of the previously-described OGS. Major differences in the test stand are:

1. Three manual pressure regulators were used instead of the 3-FPC.
2. Automatic operation was limited with only water fill and shutdown sequences being automated.
3. Electrolyte can be circulated through feed water compartments to purge liberated gas.
4. Either a DM or condenser/separators can be used for dehumidification of product gases.

The laboratory breadboard test stand was equipped with all needed TSA such as electrical power, process water source, cooling water and N_2 purge supply.

PRODUCT ASSURANCE PROGRAM

A mini-Product Assurance Program was established, implemented and maintained throughout all phases of contractual performance including design, purchasing, fabrication and testing.

Quality Assurance

Quality Assurance activities were included during the design studies, interface requirement definitions and during inspection of fabricated and purchased parts. The objective was to search out quality weaknesses and provide appropriate corrective action. Also, a quality assurance effort was involved in the preparation of the final report with the objective of identifying and resolving deficiencies that could affect the quality of future equipment.

Reliability

Reliability personnel participated in the program to insure (1) proper calibration of test equipment and TSA instrumentation, (2) adherence to test procedures and (3) proper recording and reporting of test data and observations. A survey of the subsystem and TSA design was performed to determine the calibration requirements for testing. Appropriate components were calibrated during assembly and after installation.

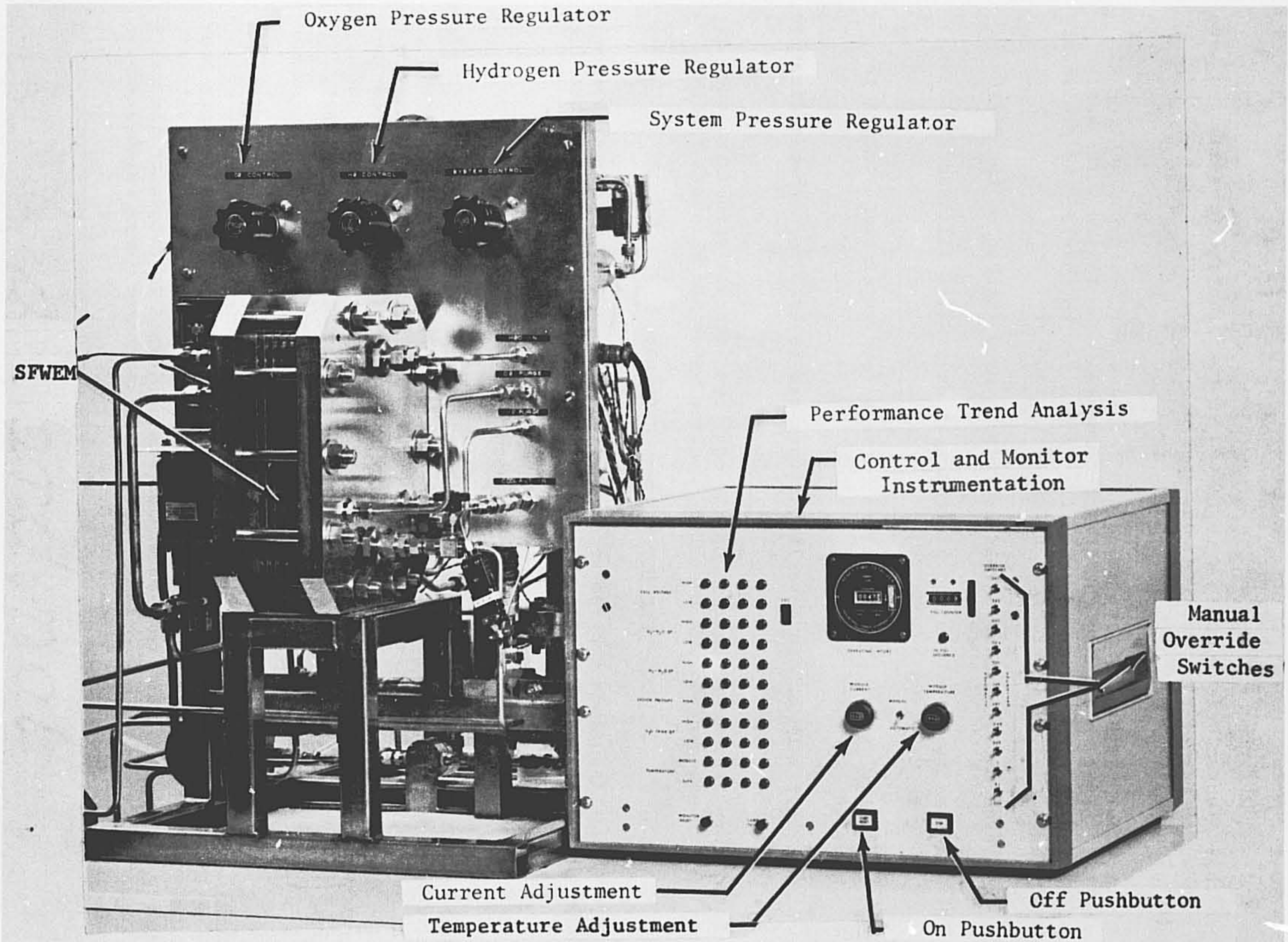


FIGURE 20 LABORATORY BREADBOARD MODULE TEST STAND

A test procedure was followed to insure that all critical parameters were properly monitored and that the testing conformed to the program's quality assurance and safety procedures. All major testing required that a test plan be completed and reviewed.

Safety

A safety program was initiated to assure adherence to safety standards and precedures essential to protect personnel and equipment. The program consisted of identifying possible adverse subsystem characteristics, reviewing designs and design changes for potential safety hazards, reviewing NASA Alerts for safety information and incorporating the equipment's protective features.

Materials Control

A mini-materials control program was initiated to provide assurance that the OGS design did not preclude the efficient application of a more detailed subsystem materials control program during subsequent developments. As a goal, materials of construction were selected to comply with projected spacecraft material specifications.

Configuration Control

A mini-configuration management program was established, implemented and maintained. This program provided for documentation concerning interface requirements for the OGS as applicable for the ARX-1 testing. The program was implemented with a primary goal to provide assurance that the efficient application of a more detailed configuration management program could be applied during subsequent developments of OGS hardware.

PROGRAM TESTING

The overall objectives of the test program were to (1) prove the integration concept of the OGS with the ARS, (2) further advance the OGS technology and (3) demonstrate the hardware maturity of the OGS components such as electrolysis cells, modules and the 3-FPC. Testing activities associated with the integrated ARX-1 and the SFWEM are presented in this section. Results of other OGS component tests will be presented in the Supporting Technology Studies section.

Integrated ARX-1 Testing

The ARX-1 testing was conducted for a period of 120 days and included testing at the component, subsystem, C/M I (hardware and software) and total system levels. Specific testing activities which occurred during the checkout, shakedown and endurance phases are shown in Figure 21.

Testing Summary

A total of 480 h (20 d) of successful, integrated ARX-1 operation in the Normal Mode was achieved. Normal Mode excludes the time required for the transitions Shutdown to Normal and of Normal to Shutdown. These transitions typically require 0.5 h each and primarily involve the pressurization or depressurization of the OGS.

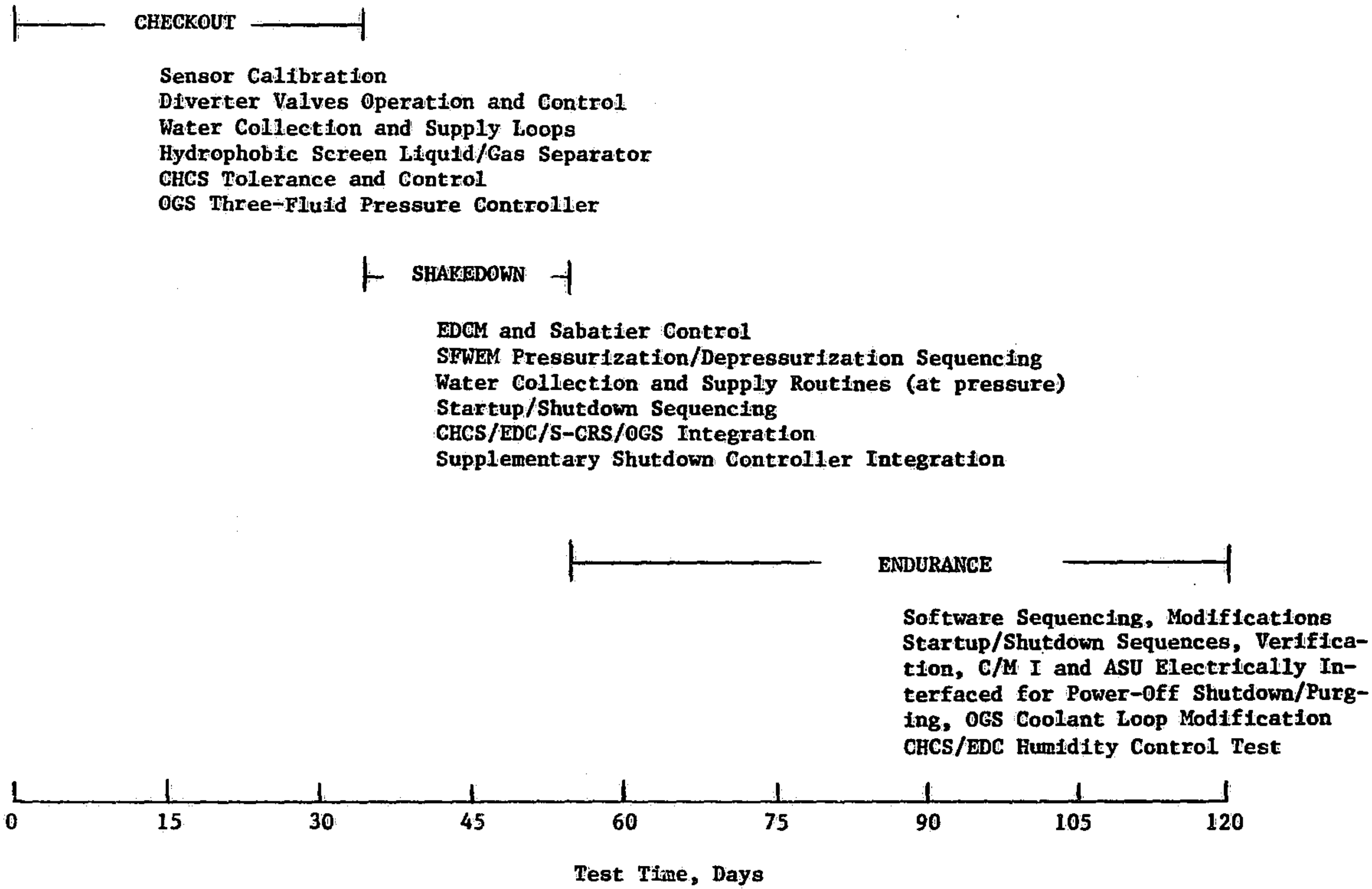


FIGURE 21 ARX-1 TEST OVERVIEW

Of the total normal operation, two seven-day periods of continuous uninterrupted operation were achieved.

The overall system performance is shown in Figure 22. The ARX-1 generated O_2 above the design level equivalent to one person's metabolic consumption plus an allowance for overboard leakage. Also, the ARX-1 removed CO_2 at greater than the one-person level. The curve for net water recovered is the algebraic total of the water (1) supplied to the OGS, (2) removed by the CHCS from the simulated cabin atmosphere and (3) removed by the S-CRS condenser/separator from the S-CRS exhaust stream.

In summary, the ARX-1 testing demonstrated the following: (1) duplicate subsystem interface components can be eliminated by treating the hardware from a single system viewpoint, (2) TSA and expendable usage can be reduced (e.g., OGS H_2 used by EDC), (3) a single integrated C/M I can simplify the collection and display of engineering data, (4) single-button startup of several integrated subsystems can be achieved, (5) the system provides real-life test conditions by determining the effects of changes in the cabin simulator on the system as a whole and (6) development and testing costs were minimized. To illustrate the last point, Figure 23 shows the total test time accumulated on the major subsystems and components of the ARX-1. Over 10,000 hours of testing have been achieved for some components using the ARX-1 as a test bed. Development of the ARX-1 as a system permitted parallel testing of key hardware elements.

OGS Performance

While Figure 22 showed the performance of the overall ARX-1 system, the OGS performance is given in greater detail in Figure 24. The nominal operating conditions for the OGS over the 480 h test period are given in Table 9. As shown, most parameters remained constant over the operating period. The electrolysis module in the ARX-1 OGS was assembled using advanced electrodes (WAB-5). The WAB-5 performance is slightly lower (higher cell voltage) than that of the super electrodes (WAB-6).

The integrated testing experienced several automatic shutdowns as listed in Table 10. Most were due to sensor or C/M I malfunctions. Two (numbers 3 and 7) were directly attributed to the OGS. One was due to the loss of coolant water and the other was a cell matrix failure which occurred during a water fill sequence. The cell matrix failure was due to out-of-tolerance pressure spikes occurring during startup and shutdown. That coupled with some pressure pertubations which occurred during the water fill damaged a cell matrix.

SFWEM Endurance Tests

The SFWEM endurance tests included testing with super electrodes (WAB-6) and with advanced electrodes (WAB-5). Both types of electrodes were assembled into two separate 12-cell modules and the modules were tested on the laboratory breadboard test stand (Figure 20) to evaluate their performances and hardware maturity.

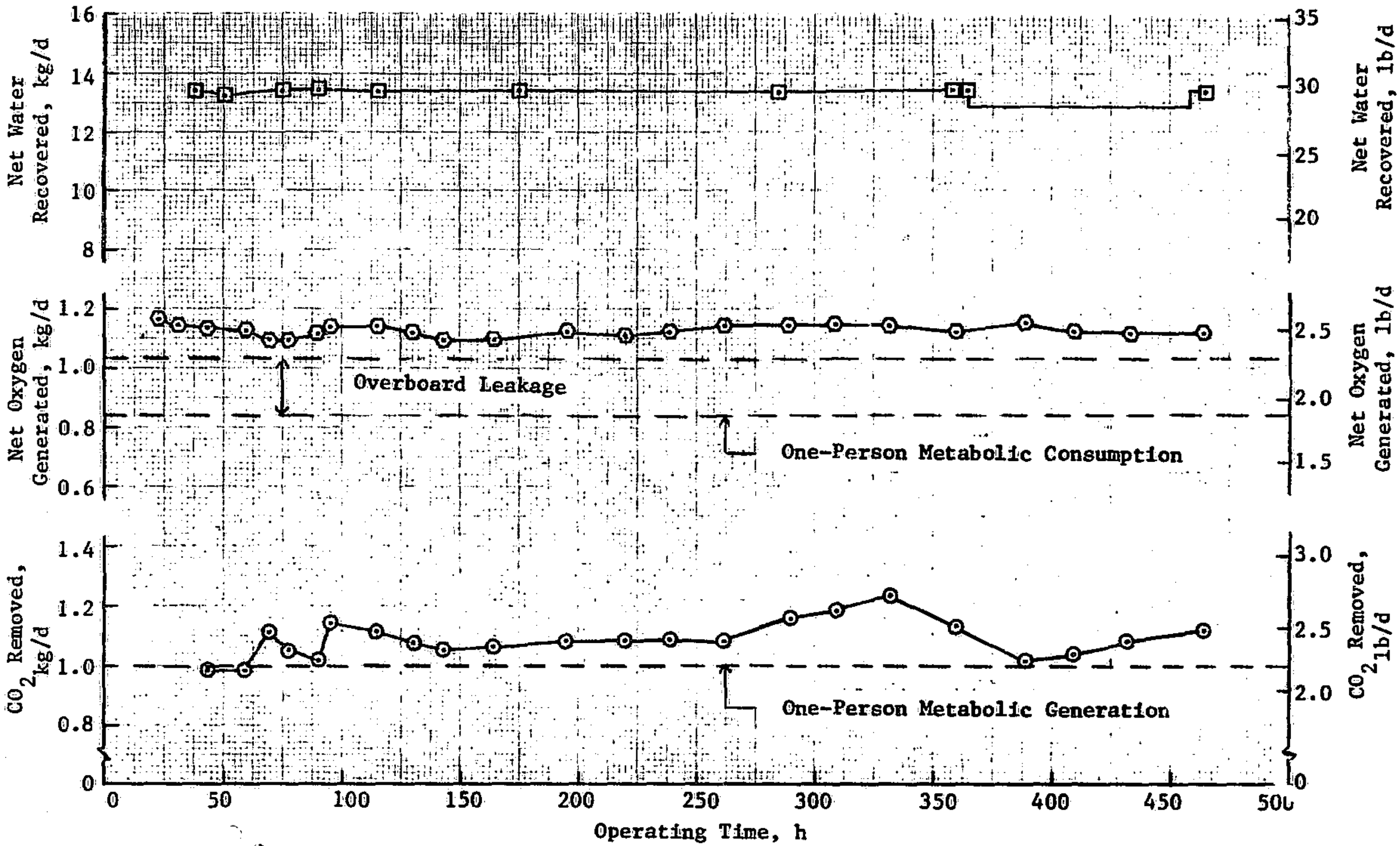


FIGURE 22 ARX-1 SYSTEM PERFORMANCE

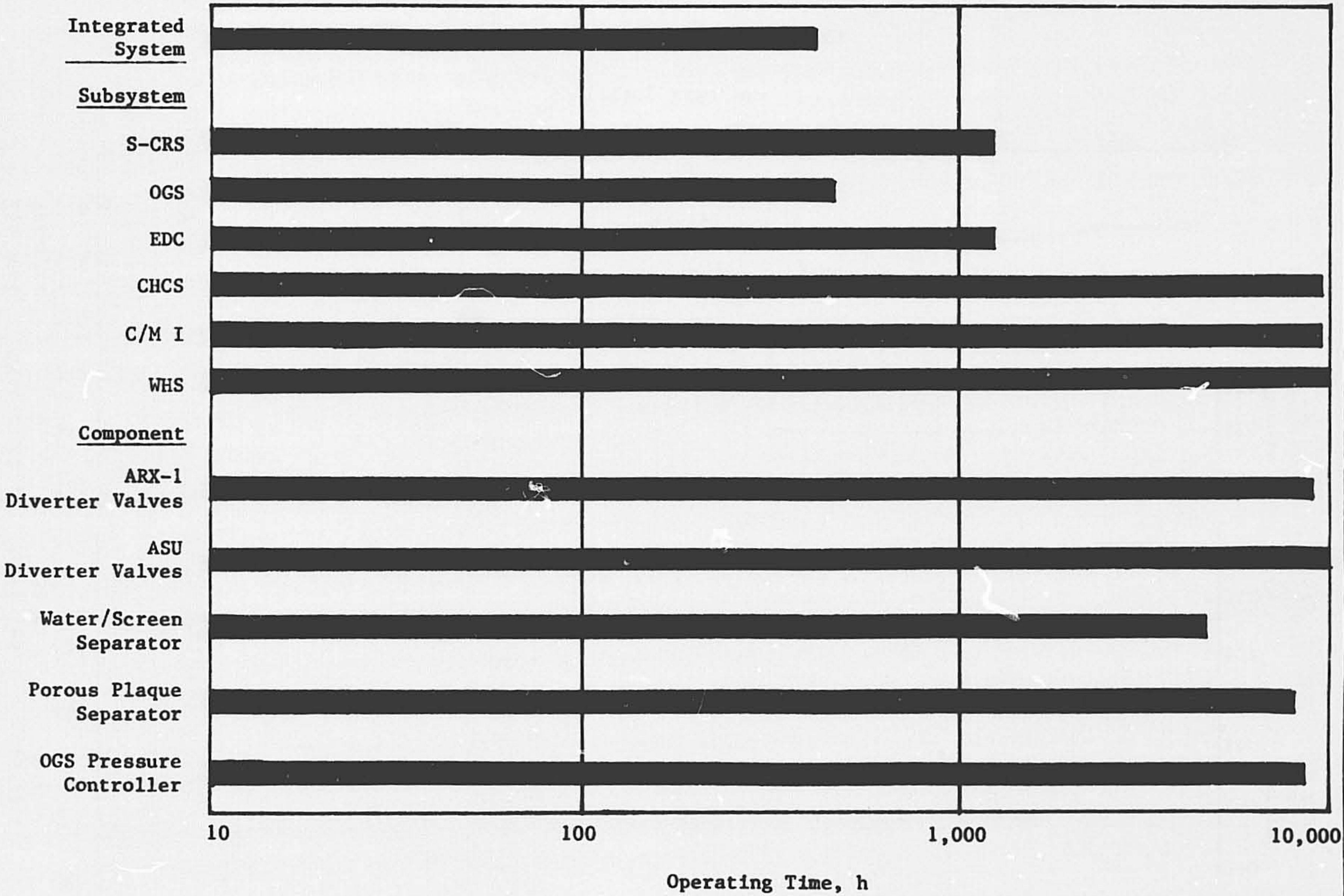


FIGURE 23 LIFE TESTING OF ARX-1 COMPONENTS/SUBSYSTEMS

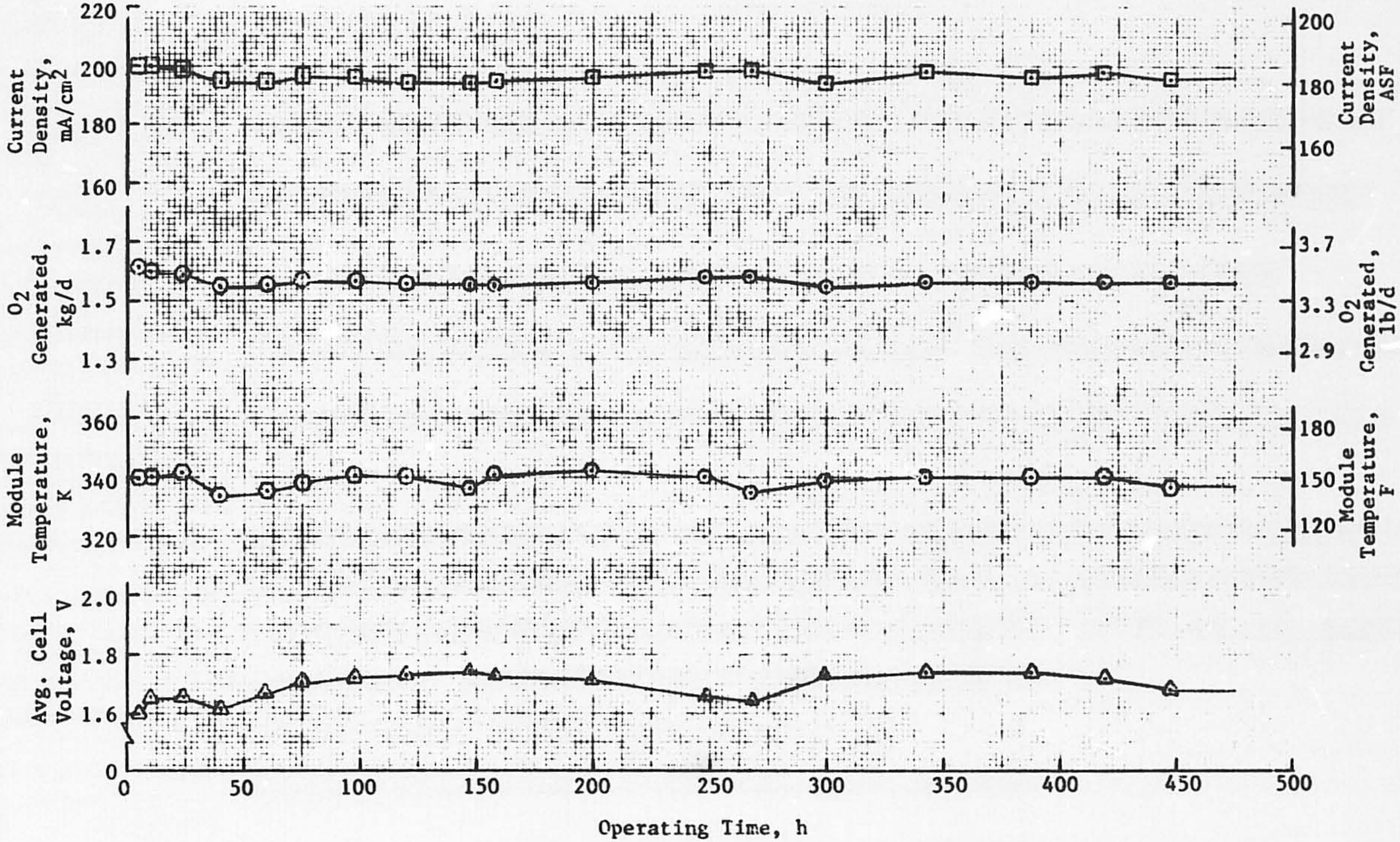


FIGURE 24 ARX-1 SFWEM PERFORMANCE

TABLE 9 OGS BASELINE OPERATING CONDITIONS

Number of Cells	12
Current Density, mA/cm^2 (ASF)	196 (182)
Coolant Temperature Control Range, K (F)	336 to 341 (145 to 155)
Pressure Control Ranges	
System Pressure, kPa (psia)	965 to 1035 (140 to 150)
H_2-to-Feed Water ΔP, kPa (psid)	15 to 19 (2.2 to 2.8)
O_2-to-Feed Water ΔP, kPa (psid)	26 to 30 (3.7 to 4.3)
Startup/Shutdown Pressurization and Depressurization Rate, kPa/min (psi/min)	37 (5.4)

TABLE 10 ARX-1 SHUTDOWN SUMMARY

No.	Time, h[a]	Cause
1	28	EDCM process air exhaust temperature sensor failure
2	32	Air Supply Unit electrical noise shutdown
3	37.5	Loss of fluid from SFWEM coolant loop
4	103.4	Supplementary shutdown controller malfunction during SFWEM feed tank fill
5	270.9	Computer halt during Normal to Standby Mode transition
6	436.4	Computer halt in Sabatier temperature control routine
7	448.4	Low SFWEM cell voltage shutdown during feed tank fill

(a) From beginning of integrated system testing

Super Electrode Testing

A 12-cell SFWEM employing super anode electrodes (WAB-6) was assembled and charged with 25% KOH (by weight) solution. Following leak checks and installation in the laboratory breadboard test stand, the feed water compartment was filled with 25% KOH solution and the module was pressurized to operating pressure by using the N_2 purge supply. The module temperature was raised by operating a startup heater and the temperature control loop. The module was then started by pressing the ON button on the control panel (Figure 20). At the start of operation the feed water tank was automatically filled with deionized water. During the normal operation it was periodically filled every six hours.

The SFWEM performance is shown in Figure 25 as a function of current density. The average cell voltage of the 12-cell module varied from 1.48 to 1.66 V as the current density was spanned from 108 to 538 mA/cm^2 (100 to 500 ASF). Both the module temperature and pressure were maintained constant at 355 K (180 F) and 993 kPa (144 psia), respectively. Exceptionally good performance (low cell voltages) was achieved.

Figure 26 shows the SFWEM performance as a function of operating time. Master test conditions are listed in the figure. The average cell voltage remained low and stable in the range of 1.47 to 1.50 V. Increase of the average cell voltage level over the 250-h testing period was negligible (only 0.02 V) considering the cell voltage variation due to temperature fluctuations.

During testing it was found that a weak spot exists in the baseline module construction in the area of the O_2 exhaust port. The weakness at this location is created by a lack of polysulfone support for the electrode assembly limiting the module's pressure differential capability. A fix has been identified and has been recommended for implementation in a follow-on program.

Readouts of individual cell voltages showed that the twelve cells performed within an exceptionally tight performance band (1.425 ± 0.015 V). The actual cell voltage distribution is shown below for two typical test times:

Cell Voltage, V	Number of Cells At 22 h	Number of Cells At 114 h
1.47	7	8
1.48	2	3
1.49	2	1
1.50	1	0

The operating conditions were the same as those listed in Figure 26 and readings were taken both at 22 h and 114 h of operation.

The exceptionally low cell voltages and their distribution indicate that the performance of super electrodes was successfully retained through scale-up from the single cell to the 12-cell module level. Refer to single cell performances under Supporting Technology Studies section of this report, but noting the difference in operating pressures. Increases in pressure will in general increase cell voltages slightly.

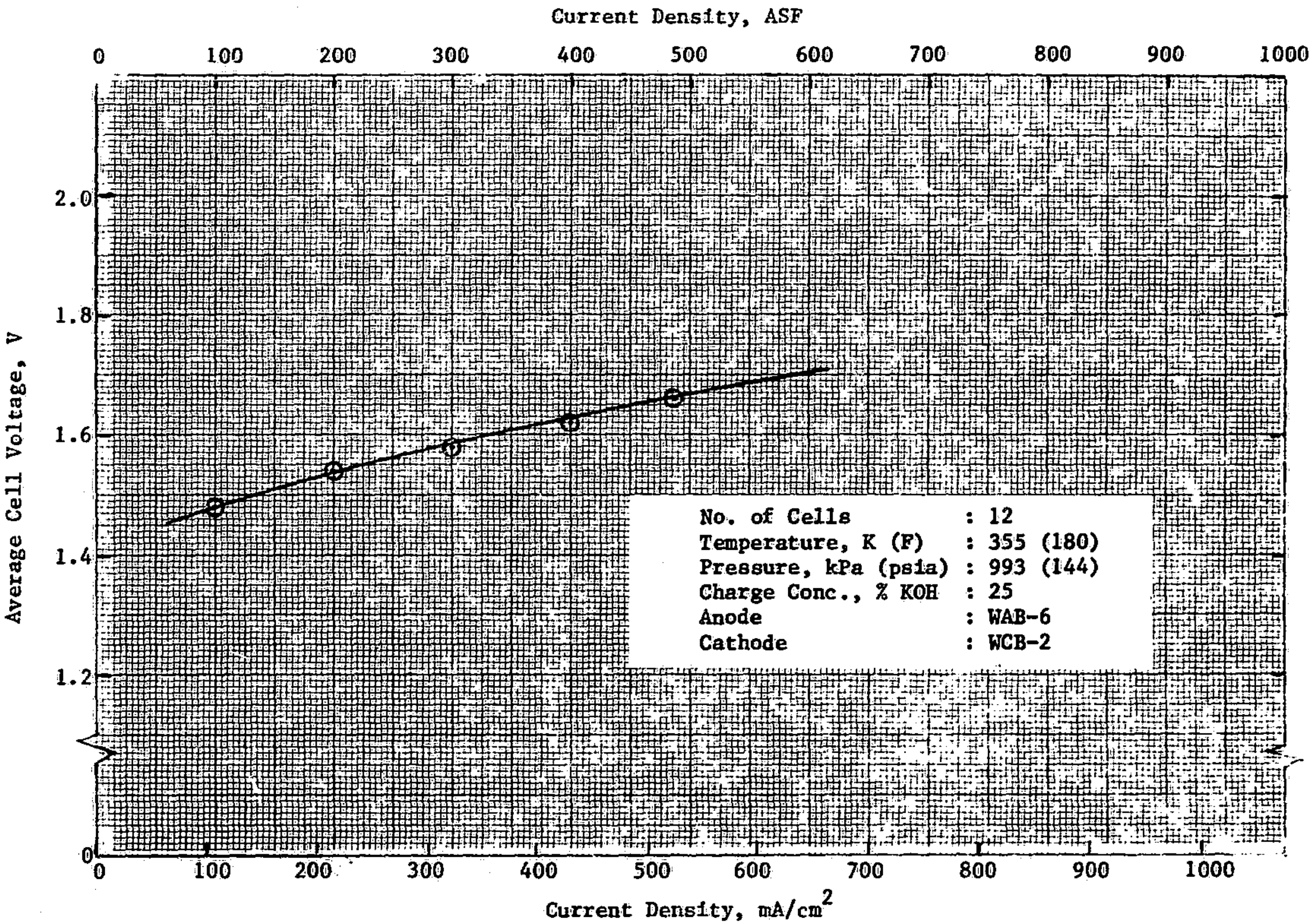


FIGURE 25 SFWEM PERFORMANCE VERSUS CURRENT DENSITY

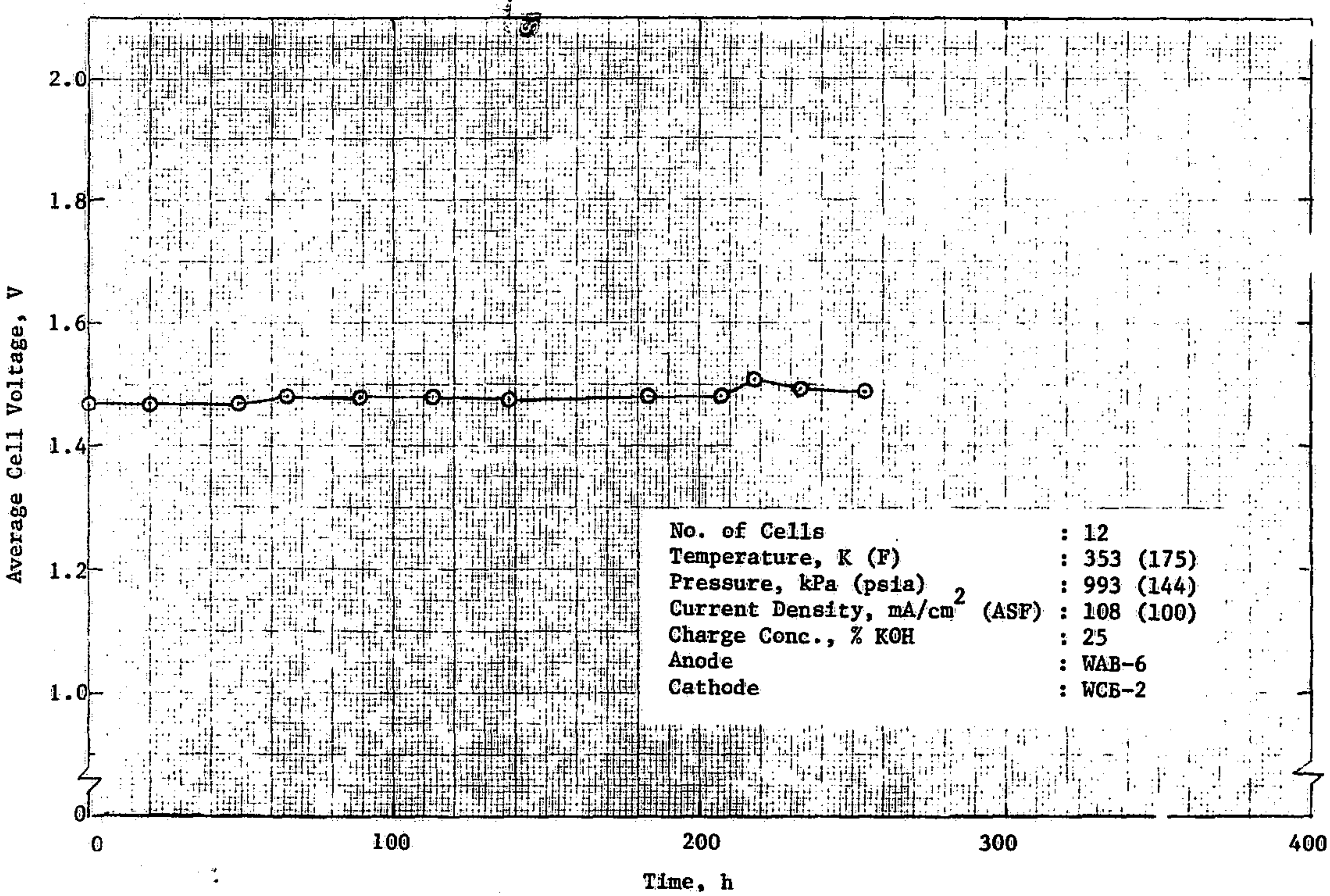


FIGURE 26 PERFORMANCE OF THE SFWEM WITH SUPER ELECTRODES

Advanced Electrode Testing

A separate, 12-cell SFWEM was assembled and tested using advanced anodes (WAB-5). The test procedures were the same as for the super electrode testing. The performance of the advanced electrodes is presented in Figure 27 along with operating conditions. Though the average cell voltage was slightly higher than that of the super electrodes it remained stable at around 1.58 V throughout the testing period. Several shutdowns were experienced during the 120-day testing period. Most of these shutdowns were, however, related to malfunctions of instrumentation and test stand components, other than the module itself, such as feed pump, coolant pump and solenoid valves. The test stand was built six years ago. It is conceivable that a number of aged components need repair or refurbishment.

SUPPORTING TECHNOLOGY STUDIES

A variety of supporting studies were performed to ensure that the OGS was successfully developed and integrated into the ARX-1. Some activities, such as those related to developments of electronics, instrumentation and super electrodes, were covered in the previous sections. This section presents results of four major supporting studies: (1) single-cell endurance tests, (2) 3-FPC tests, (3) product gas dehumidification analysis and (4) elimination of stray electrolysis in the coolant loop.

Single Cell Endurance Tests

As part of the testing activities to demonstrate the hardware maturity of the OGS, a single cell was assembled with one of the super anode electrodes (WAB-6) and endurance tested in a single-cell test stand. A flow schematic of the single-cell test stand was presented in a previous report[4] and the cell components are identical to those presented in Figure 9.

A total of 8,650 h of the single cell operation had been accumulated at the conclusion of the current program. Performance during the period of endurance testing is presented in Figure 28. Operating conditions were set nominally at 352 K (175 F), 161 mA/cm^2 (150 ASF) and ambient pressure. Only during the period between 720 to 1,440 h (specified as "A" in Figure 28) was the current density set at 323 mA/cm^2 (300 ASF). Slight fluctuations on the cell voltage level were mostly due to minor temperature variations. A net voltage change of only 4.6×10^{-6} V/h was observed over the last 6,500 h. It is noted that the cell voltage levels remained constant during the last 3,000-h period. Throughout the testing there were only two interruptions excluding the building power failures. One was due to a pump failure and the other was an intentional shutdown during the transition period from the previous program and to the current one. The initial 1,440-h testing was conducted under the previous program (Contract NAS2-8682).[4]

The effect of the current density on cell voltage is presented in Figure 29 at different load times for the same electrode used for the above endurance testing. The test conditions also were maintained the same. The performance range of the super electrode is at least 10% better than the state-of-the-art performances (also, see comparisons in Figure 1).

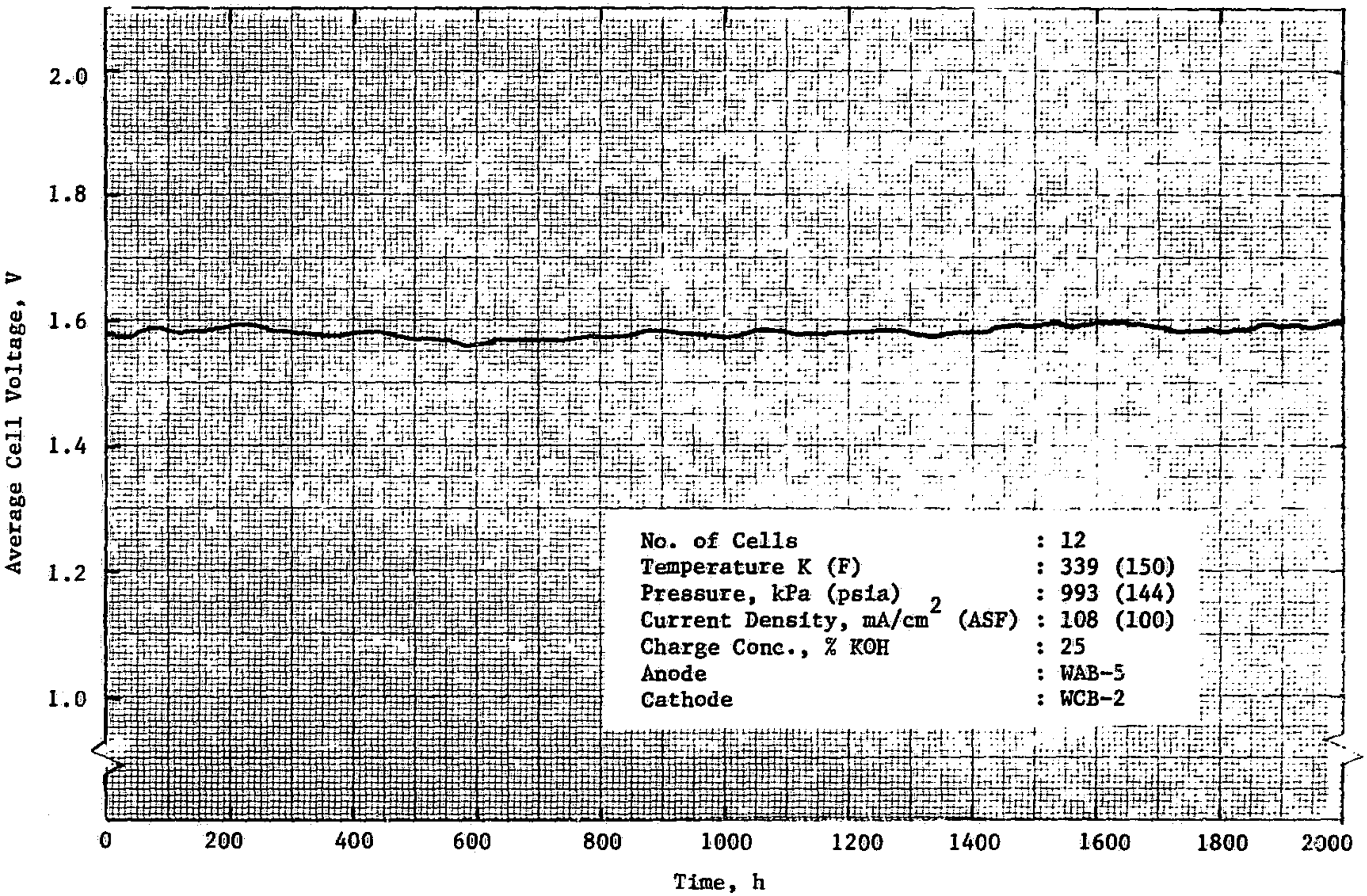


FIGURE 27 PERFORMANCE OF THE SFWEM WITH ADVANCED ELECTRODES

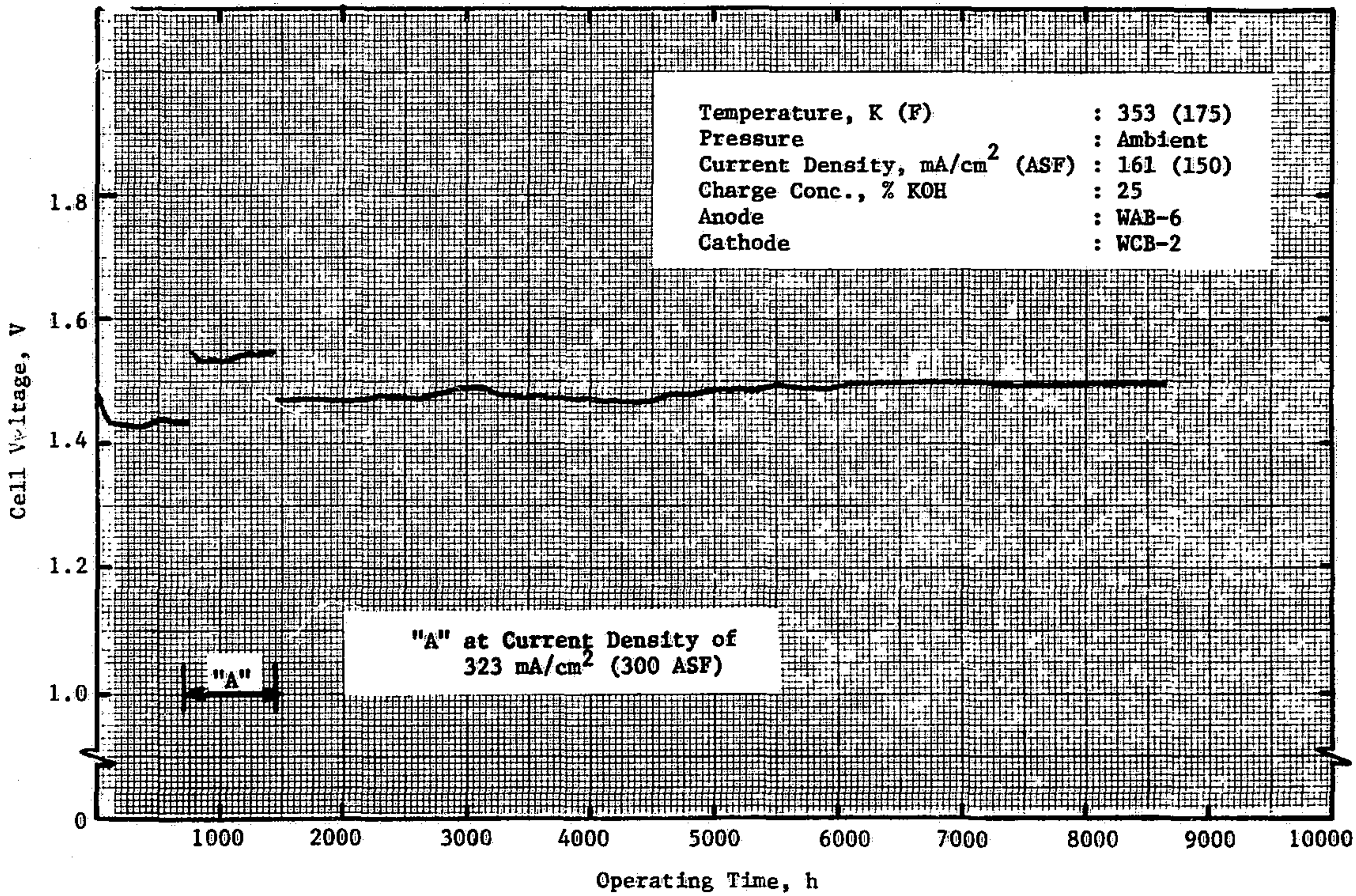


FIGURE 28 SINGLE CELL PERFORMANCE DURING ENDURANCE TEST

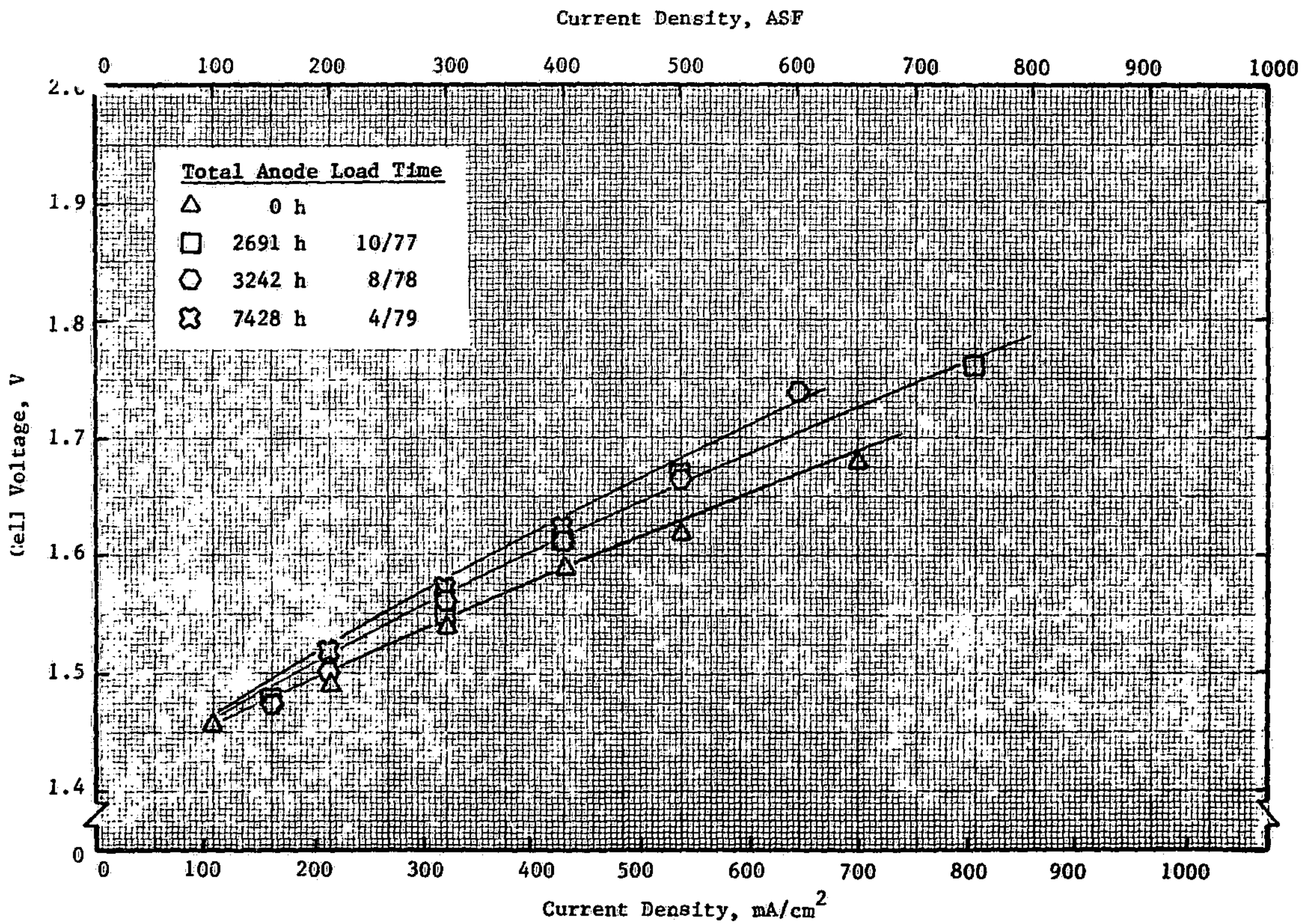


FIGURE 29 SUPER ELECTRODE PERFORMANCE VERSUS CURRENT DENSITY

Three-Fluid Pressure Controller Tests

The 3-FPC of the OGS was extensively tested (approximately 9000 h) as part of the ARX-1 test program. The ARX-1 provided a "real-life" test facility since it combined all three major elements of the controller (mechanical, electrical and software) in one location. The mechanical portion consisted of the motor-driven regulators and sources of O_2 and H_2 from the OGS at the design flow rates. In addition, the time variations of the flow rates as they occur during a water feed tank fill (i.e., flows cease) were implemented. The electrical elements were the pressure transducers, their signal conditioning and motor drive circuitry. The software contained the control routines for actuating the regulators in response to pressure level inputs.

Early in the testing phase it was found that the originally selected miniature, solid-state, differential pressure transducers exhibited certain undesirable characteristics. While the sensed pressure differentials were reproducible, the response level was found to be a function of absolute pressure. Figure 30 illustrates the typical behavior. A mechanical transducer (ordinate) reading is compared to the solid state transducer (abscissa) reading at various system pressures. Ideally, all curves would be congruent, have positive slopes and pass through the origin. Only the curve for zero system pressure (atmospheric pressure) had a positive slope. The intercept can be adjusted with signal conditioning. At other pressures, however, the data showed large scatter and slope changes as a function of pressure. The severity of the changes as well as the data scatter precluded use of the miniature pressure transducers of the type originally selected. The control of the SFWEM internal cavity pressures and pressure differentials are sufficiently critical that reliable transducers are needed. It was for this reason that the controller was modified to accept mechanical transducers with electrical outputs to complete the testing. There were no further problems with pressure sensing.

Another aspect of the controller testing was selection of the proper parameters in the software control routines to obtain the desired dynamic response in the regulators. Complex interactions among regulator seat travel, rotation rate, gas flow rate, pressure and control parameters (such as signal sample time, response time, response rate and waiting periods between successive regulator stepping) were analyzed and evaluated. Adjustments were made so that the OGS would experience only pressure changes within the tolerance band during startup pressurization, normal operation and shutdown depressurization. Table 11 summarizes the operating conditions of the controller that were used during most of the testing.

Several areas were identified for additional improvements and modification of the controller. Vendor discussions indicated that solid-state pressure transducers can be found which will give the required performance. Additional analysis is required to relate control routine parameters with mechanical aspects such as orifice sizes, valve thread size and pitch, flow rates and pressure levels, so that optimum conditions can be established for any capacity OGS. Also, the weight of the controller can be reduced and the package streamlined. These modifications have been recommended for follow-on activities.

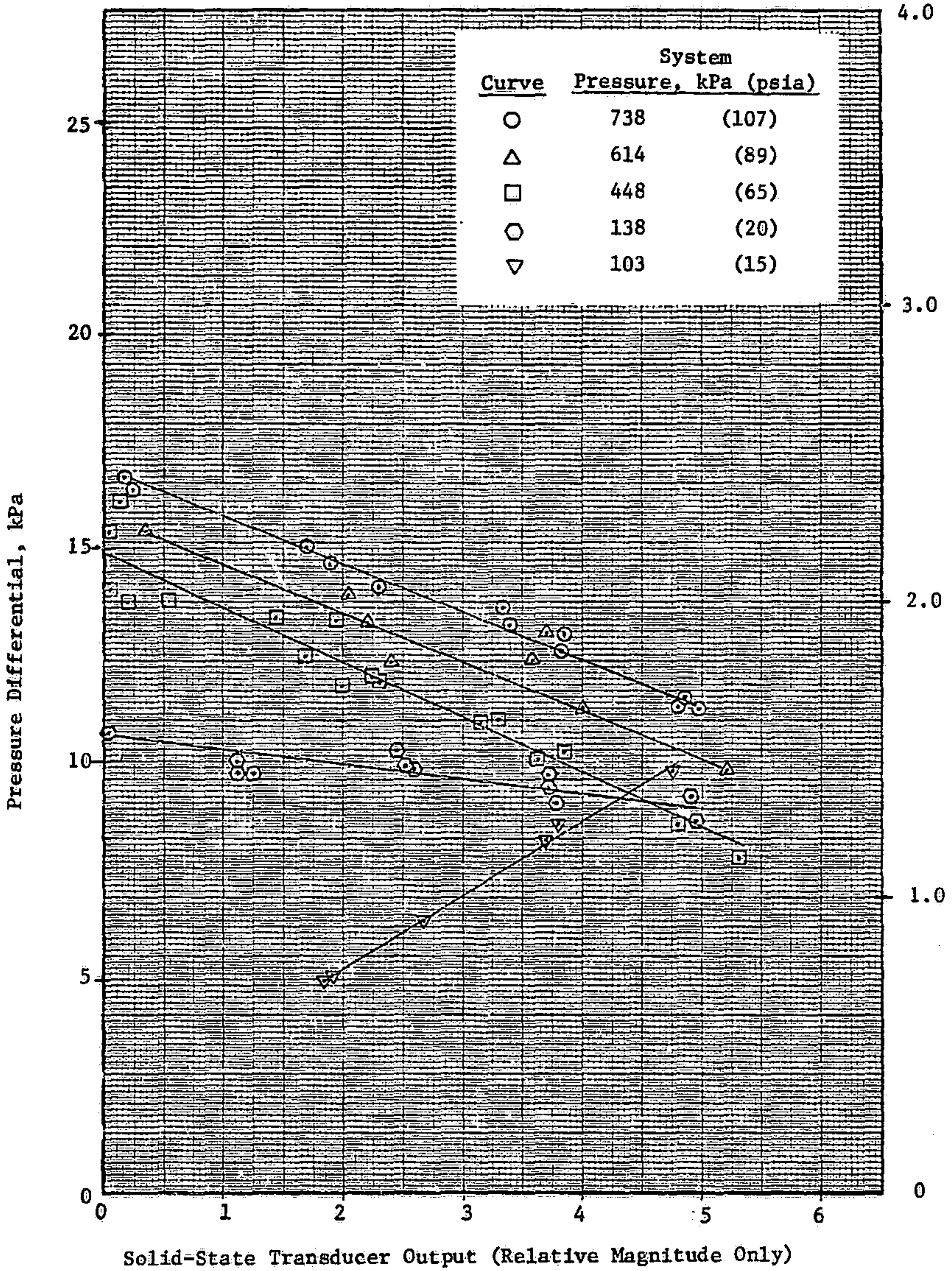


FIGURE 30 THREE-FLUID PRESSURE CONTROLLER – SOLID STATE TRANSDUCER CHARACTERISTICS

TABLE 11 THREE-FLUID PRESSURE CONTROLLER NOMINAL OPERATING CONDITIONS

Characteristic	Regulator System	Regulator O_2	Regulator H_2
A. Mechanical			
Gas Type	O_2	O_2	H_2
Upstream Pressure, kPa (psia)	1035 (150)	1060 (154)	1050 (152)
Downstream Pressure, kPa (psia)	103 (15)	1035 (150)	114 (16.5)
Upstream-to-Water Feed ΔP, kPa (psid)	0	28 (4.0)	17 (2.5)
Mass Flow Rate, g/min (lb/d)	1.07 (3.4)	1.07 (3.4)	0.134 (0.42)
Volumetric Flow, slpm (scfm)	0.8 (0.028)	0.8 (0.028)	1.6 (0.056)
B. Control			
Actuation Time[a], s	0.1 (Max)	13.6	7.6
Minimum Waiting Period[b], s	10	40	23

(a) Time for regulator to respond to 6.9 kPa (1 psid) sensed differential pressure. Response only occurs if level is not within control range.
(b) Between successive regulator advances.

Product Gas Dehumidification Analysis

Past development efforts of water electrolysis-based OGS's identified dew point control of product gases as one of the obstacles to be overcome. Dehumidification of product gases from water electrolysis subsystems is necessary when the product gases have a dew point greater than the maximum allowable dew point level within the cabin or greater than their dry bulb temperatures. Generally the spacecraft atmosphere requires that the dew point of the OGS product gases (H_2 and O_2) should be lower than 287 K (57 F).[2]

Direct application of conventional condenser/separators to the water vapor removal from the OGS product gases was not deemed desirable because of the zero gravity environment. Three techniques among various approaches to solve the problem have been considered to be the most practical. These are:

1. Low temperature operation
2. Electrolytic dehumidification
3. Line heating with the gas expansion

The previous programs (Contracts NAS2-7470 and NAS2-8682) have focused on further development of the electrolytic dehumidification concept.[2,4]

Concept Descriptions

The dew point of the product gases is a function of the operating conditions of the water electrolysis module such as temperature, pressure and KOH concentration. Their effects on the product gas dew point are presented in Figure 31. The dew point can be reduced either by increasing operating pressure and the KOH concentration or by decreasing operating temperature.

Low Temperature Operation. The dew point of 287 K (57 F) corresponds to a water vapor pressure of 1.60 kPa (12 mm Hg). This vapor pressure level can be obtained directly within the module itself by decreasing temperature. For example, the water vapor partial pressure of a gas saturated with a 33.3% KOH (by weight) solution at 297.6 K (75.7 F) and 101 kPa (14.7 psia) is 1.60 kPa (12 mm Hg) which corresponds to a dew point of 287 K (57 F) at 101 kPa (14.7 psia).

Though this method is the simplest and most reliable among the three methods considered, it has been eliminated due to high power needs (increased cell voltage) at low temperatures. The driving force (water vapor pressure gradient) for the water vapor transport is also low at lower temperatures, resulting in current density limitations.

Electrolytic Dehumidification (ED). The ED concept uses water vapor electrolysis to remove the water vapor carried with the product gases. The O_2 and H_2 from the main electrolysis module are passed respectively through the anode and cathode cavities of the water vapor electrolysis cells of the ED module. Water vapor is then absorbed in electrolyte and electrolyzed to form additional O_2 and H_2. Detailed descriptions of the ED concept and its development activities are presented elsewhere.[2,4]

The water vapor electrolysis of ambient air is a proven technology. Technical feasibility of its application for dehumidification of the OGS product gases was demonstrated.[2,4]

One advantage of the ED concept is the almost total utilization of water processed by the main electrolysis system, including the water vapor normally carried away with the product gas streams. By operating the electrolytic dehumidifier upstream of any system pressure regulators, trace heating of lines and regulators can be eliminated. Another advantage is the ED in combination with gas expansion will produce much drier gases than other techniques.

Disadvantages of the ED concept are requirements of water vapor electrolysis cells, additional power supply and control/monitor instrumentation, and possible increases in maintenance requirements.

Line Heating with Gas Expansion. The partial pressure of water vapor in a given gas mixture is directly proportional to the total gas pressure. Accordingly, one simple way of reducing the partial pressure of water vapor is to reduce the total gas pressure through gas expansion. For example, the dew point of 287 K (57 F) can be achieved by operating the electrolysis module at 1.24×10^3 kPa (180 psia), 353 K (175 F) and 40% KOH concentration (see Figure 31). In order to prevent water vapor from condensing in the product gas line, pressure regulators and the lines between the module and regulators may have to be heated depending on the operating temperature and ambient conditions.

Advantages of this technique are the simplicity of the concept and its operation, less hardware complexity and weight, and virtually no maintenance requirements.

Disadvantages are those associated with higher pressure operation and requirements for component heating and additional insulation. These disadvantages can be lessened by mounting the pressure regulators close to the module to limit line lengths and heating requirements.

Selected Approach

Among the three practical approaches described, the first method is definitely the simplest one. However, it was eliminated from further consideration because of the greater power penalty and operational current density limitations. The other two methods are equally attractive and are comparable in many ways. Qualitative comparisons are summarized in Table 12 with the "X" marked technique being considered to be slightly more favorable. In overall, the line heating approach is favored.

Quantitative comparisons of the two methods were made by the use of overall energy balances for a three-person capacity OGS. Design details of the three-person capacity OGS can be found elsewhere.[4,7] Operating conditions, used as a basis in the energy balance calculations, are presented in Table 13. Results of the energy balance calculations are presented in Table 14. Liquid phase water at 298 K (77 F) was taken as a reference state. Heat losses were estimated by assuming that heated components were covered with 5.1 cm (2 in)-thick

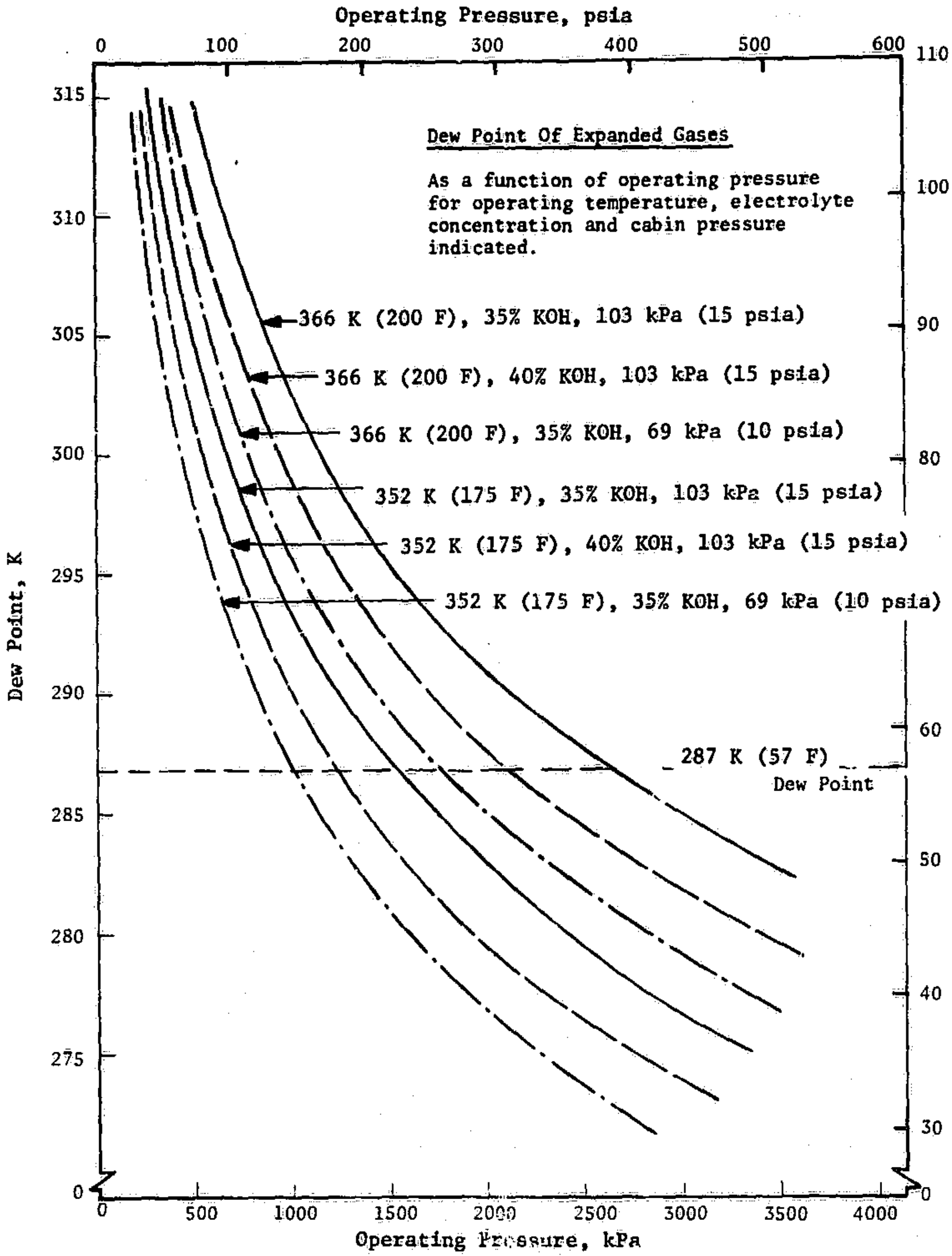


FIGURE 31 PRODUCT GAS DEW POINT

TABLE 12 COMPARISON OF ED AND LINE HEATING APPROACH FOR DEHUMIDIFICATION

Category	ED	Line Heating	Remarks
Overall System Hardware			
Weight		X[a]	
Simplicity (No. of parts)		X	
Power Requirement		X	Very close
Heat Rejection		X	Very close
Maintenance		X	
Reliability		X	
Flexibilities in Operational Temperatures	X		LH has a limit
Dew Point of Product Gases	X		

(a) More favorable approach is marked by "X"

TABLE 13 OPERATING CONDITIONS AND CHARACTERISTICS OF A THREE-PERSON CAPACITY OGS

Descriptions	ED	Line Heating
Cell Area, cm^2 (ft^2)	92.9 (0.1)	92.9 (0.1)
No. of Cells	33	30
Current Density, mA/cm^2 (ASF)		
SFWEM	206 (191)	210 (195)
EDM	47 (44)	Not Applicable
Temperature, K (F)	356 (180)	356 (180)
Pressure, kPa (psia)	965 (140)	2141 (180)
O_2 Production, kg/d (lb/d)	4.19 (9.24)	4.19 (9.24)
H_2 Production, kg/d (lb/d)	0.53 (1.16)	0.53 (1.16)
Average Cell Voltage, V		
SFWEM	1.5	1.5
EDM	1.65	Not Applicable
Product Gas Temp., K (F)	317 (110)	317 (110)
Feed Water Temp., K (F)	294 (70)	294 (70)

TABLE 14 SUMMARY OF ENERGY BALANCES

(Basis: 1 day of operation; Reference temperature, 298 K (77 F))

Electrolytic Dehumidification (ED)

Description	Input kcal (Btu)	Output kcal (Btu)
• Enthalphy of H_2O	-19 (-74)	
• Enthalpy of Products		117 (465)
• Electricity (881 W)	18,203 (72,178)	
• Standard Heat of Reaction		17,899 (70,972)
• Heating (20 W)	412 (1,632)	
• Heat Losses (Penalty 28 W)		580 (2,300)
Total	18,596 (73,736)	18,596 (73,737)

Line Heating

Description	Input kcal (Btu)	Output kcal (Btu)
• Enthalpy of H_2O	-19 (-74)	
• Enthalpy of Products		117 (465)
• Electricity (878 W)	18,123 (71,861)	
• Standard Heat of Reaction		17,899 (70,972)
• Heating (20 W)	416 (1,650)	
• Heat Losses (24 W)		504 (2,000)
Total	18,520 (73,437)	18,520 (73,437)

Comparison of Weight Penalties

Description	ED	Line Heating
• Fixed Hardware[(a)], kg (lb)	9 (20)	1 (2)
• Power Penalty[(b)] (DC), kg (lb)	242 (534)	241 (531)
• Heat Rejection Penalty, kg (lb)	6 (13)	5 (11)
Total	257 (567)	247 (544)

(a) Dehumidifying section only. Fixed hardware weight of the rest of the subsystem should be the same for both cases.

(b) Based on 0.268 kg/W (0.590 lb/W) for DC power and 0.198 kg/W (0.436 lb/W) for heat rejection. AC power penalty for instrumentation was not considered. Would be approximately the same for either approach.

Min-K insulation and highly polished aluminum shield. Results of the weight penalties comparison indicate that the total weight penalty for line heating would be approximately 10 kg (22 lb) less than that of electrolytic dehumidification.

In conclusion, both ED and line heating approaches are technically feasible and equally attractive in some ways. However, close comparison reveals that the line heating technique is slightly more favored with less total weight penalty, less system complexity and less maintenance requirements. Accordingly it was recommended that the line heating should be baselined for the OGS and that the ED be kept as a backup.

Elimination of Stray Electrolysis in the Coolant Loop

During the endurance testing of a 12-cell SFWEM it was observed that corrosion was occurring in the last coolant compartment bipolar plate. This corrosion was identified as a result of unwanted stray electrolysis in the coolant loop due to a high potential difference between the last current collector (approximately at 20 V) and the end plate (at zero electrical potential). Such a high potential difference across a common liquid coolant medium (water) caused the water to be electrolyzed.

The stray electrolysis in the coolant loop had not been observed previously while testing prior electrolysis modules consisting of six cells or less. For six-cell modules the voltage between the last cell on the high voltage end and the endplate was less than 10 V. With the 12-cell modules the voltage differential is closer to 20 V.

The insulation utilized between the last current collector and the endplate was adequate to withstand 10 V but is not able to withstand the near 20 V. As a result, a corrosion current flow occurs involving metal ion dissolution, meaning metal is oxidized and water reduced.

Since future subsystems will have more than 12 cells per module this problem must be eliminated. In order to correct this problem a special fluid line connector, similar to that used for the water feed compartment interface, was fabricated and installed to provide for at least a 5 cm (2 in) insulation between the metallic components. Subsequent tests indicated that the modification effectively eliminated the stray electrolysis problem.

CONCLUSIONS

The following conclusions are direct results of the program activities:

1. Integrated testing of the OGS and the WHS with the ARX-1 has demonstrated that the integration concept of the ARS is feasible.

2. An OGS using the SFWE concept has a potential of being one of the simplest and most reliable OGS's with low weight and power penalties.

3. The Contractor-developed super anode electrodes (WAB-6) have made it possible to reduce the power consumption of state-of-the-art water electrolysis by approximately 10%.

4. The WAB-6 super electrodes have been endurance-tested for more than 8,650 hours. Thoughout the endurance testing, the performance of the electrodes has been steady and no indication of degradation has been observed.

5. The performance of WAB-6 electrodes has been demonstrated to be reproducible. Twelve super electrodes have been fabricated and tested under this program. Performances of these electrodes varied in the range of 1.47 to 1.50 V at 355 K (180 F), 993 kPa (144 psia) and 161 mA/cm^2 (150 ASF).

6. Automatic operation of the 3-FPC, including system pressurization and depressurization, has been demonstrated.

7. Hardware and the subsystem technology have been demonstrated to be ready for demonstration at the preprototype level.

RECOMMENDATIONS

Based on the work completed, the following recommendations are made:

1. Incorporate all the technology advances in static feed water electrolysis including cells, modules and subsystems into one, self-contained engineering prototype OGS.

2. Further advance the SFWE-based OGS technology by demonstrating methods for KOH elimination from feed water compartments and for elimination of stray electrolysis in the coolant loop. Modify the current cell design to strengthen the O_2 exhaust port and to increase pressure differential capability.

3. Endurance test the engineering prototype OGS to further demonstrate the system technology and the hardware maturity. Demonstrate cyclic operation under typical day/night time frames expected of a Habitability Module.

4. Further characterize performance of the super electrodes under various test conditions such as current density, temperature and pressure and over extended periods of time.

5. Conduct parametric testing of the OGS to generate data needed to optimize the OGS. This is particularly important because the OGS requires the greatest expenditure of power among the five subsystems of an ARS.

6. Characterize the 3-FPC, expand its operation over the range of ambient to 1,380 kPa (200 psia) and endurance test to ensure its availability for future NASA needs.

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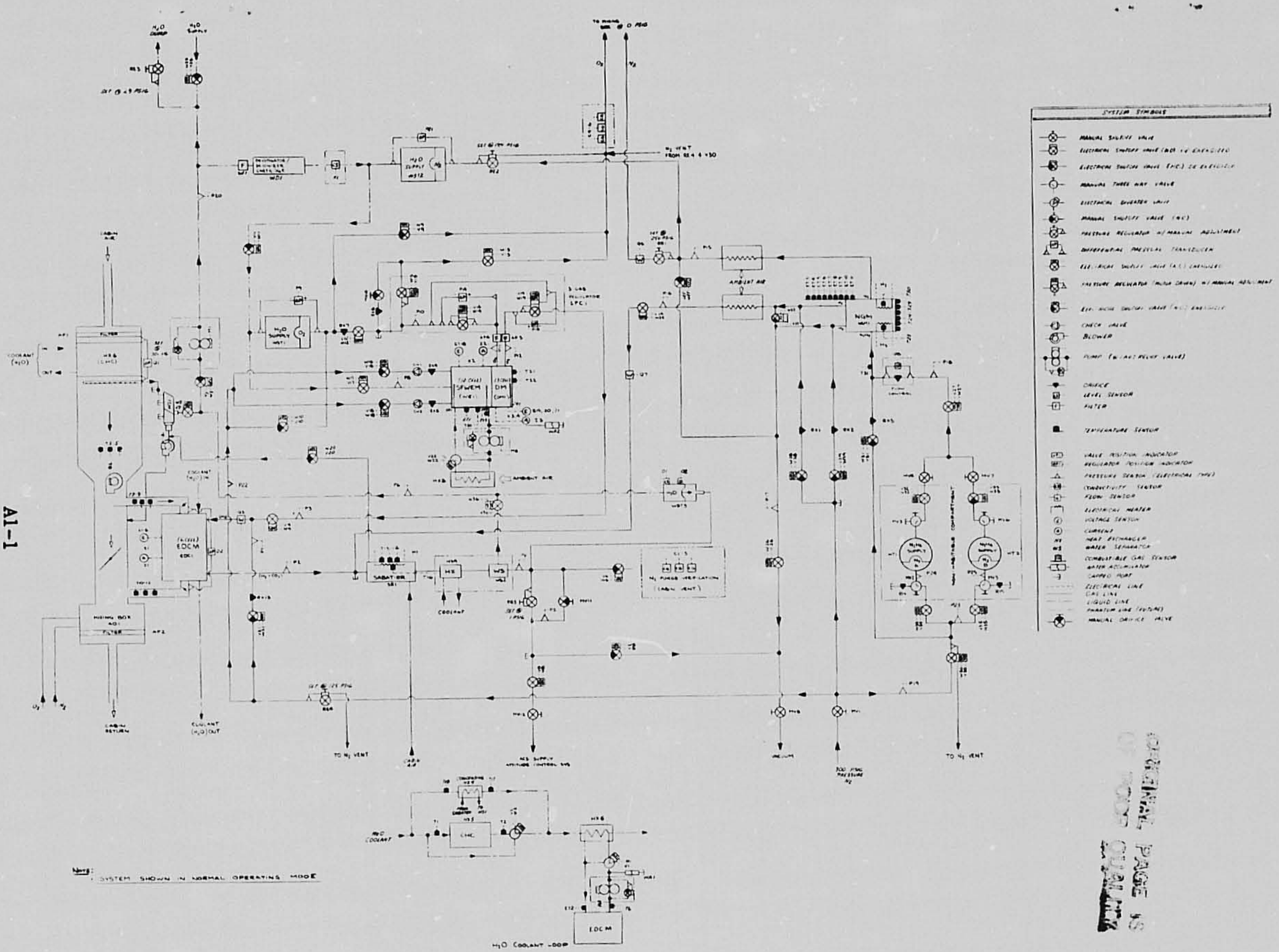

APPENDIX 1 ARX-1 FLOW SCHEMATIC

APPENDIX 2 ARX-1 OPERATING MODES DEFINITIONS

Shutdown Mode (B)

The ARX-1 is not generating O_2 or N_2 and not removing CO_2 or moisture from the air. The process air blower is off as is the water separator blower. The currents in the three modules are off, the system is completely depressurized to atmospheric pressure and the Sabatier reactor and N_2 generation modules are cold. The system is powered and all sensors are operating. The CHCS, EDCM and OGS temperature control loops are operating. The shutdown mode is called for by any of 92 monitored parameters exceeding tolerance, manual actuation or unsuccessful mode transition.

Normal Mode (A)

The ARX-1 is generating O_2 and N_2 and removing CO_2 and water vapor from the air. The CO_2 removed from the air is reduced by the Sabatier reactor to water and methane. The excess water collected is delivered to an external water tank. The Normal Mode is called for by manual actuation.

Standby Mode (E)

The ARX-1 is operating essentially as it is in the Normal Mode with the exception that the EDCM and SFWE currents are zero, the process air blower and water separator blowers are off and the SFWEM pressure is maintained by N_2 through the purge valves. The Standby Mode is called for by manual actuation.

Purge Mode (C)

The ARX-1 is being purged with external N_2 through all H_2-carrying lines, H_2 module cavities, O_2-carrying lines and O_2 module cavities. All module currents and blowers are off as are the Sabatier and N_2 generator module heaters. The system has N_2 pressure in it. This is a continuous purge and will remain until a new mode is called for. The Purge Mode is called for by manual actuation.

Unpowered Mode (D)

No electrical power is supplied to the ARX-1 C/M I. Thus, no electrical power is applied to the ARX-1 mechanical/electrochemical hardware. The system is not operating however, there could be N_2, H_2 or O_2 pressure in the system and there could be N_2 flows through the system depending on how the unpowered condition was arrived at. The Unpowered Mode is called for by manual actuation (circuit breaker in TSA) or an electrical power failure.